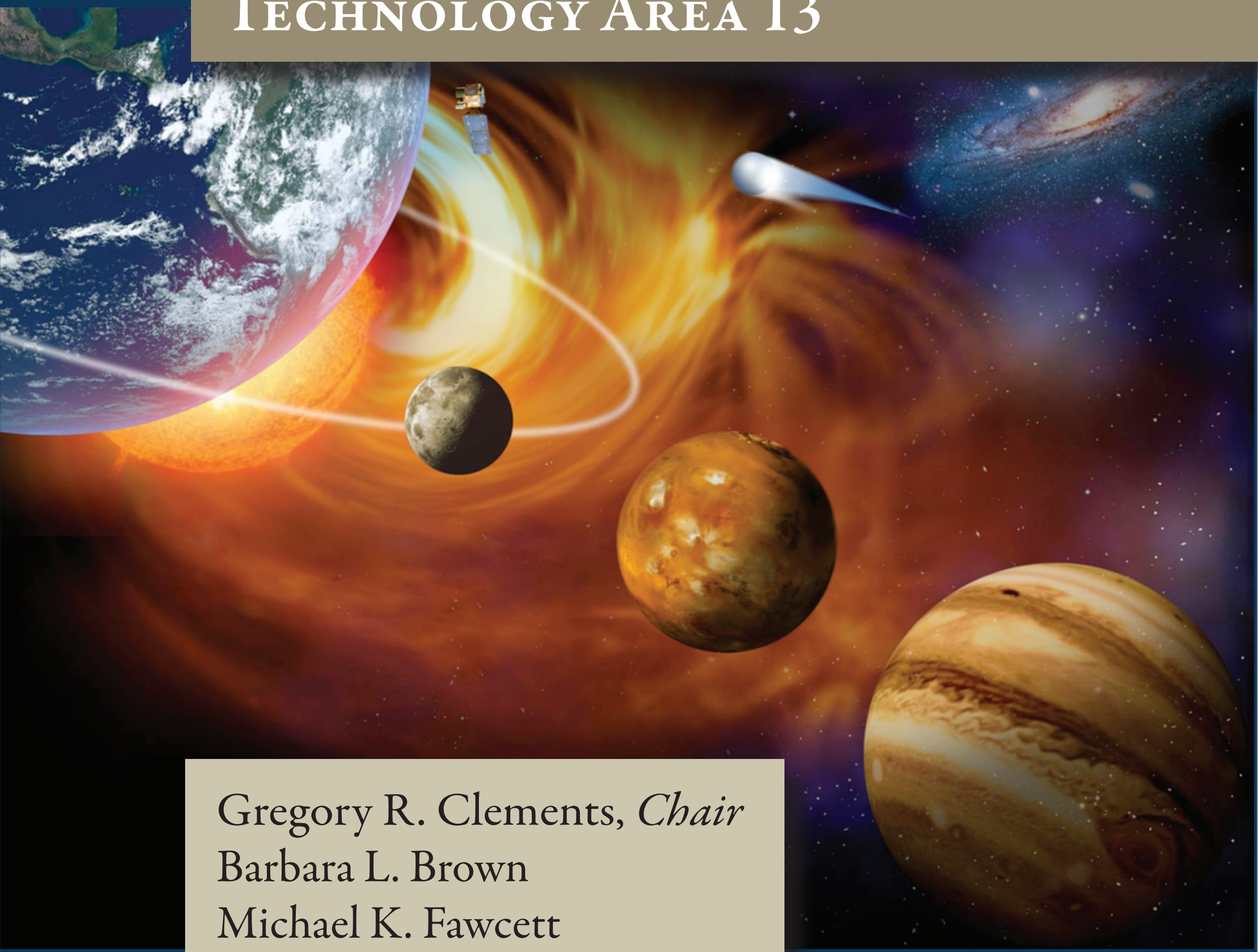
National Aeronautics and Space Administration

Ground and Launch Systems Processing Roadmap

Technology Area 13



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FOREWORD

NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation's current capabilities. The present state of this effort is documented in NASA's DRAFT Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA's space technology activities. This document presents the DRAFT Technology Area 13 input: Ground and Launch Systems Processing. NASA developed this DRAFT Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.

EXECUTIVE SUMMARY

Without sufficient investments in innovative technologies to radically change Ground and Launch Systems Processing (GLSP), NASA will fall short of its space exploration goals. Since operations costs can constitute roughly 40% of the total mission costs, by realizing savings in this area, NASA could redirect significant investments toward supporting a broader customer base with robust exploration missions. Theoretically, a "ship and shoot" approach to ground and launch processing is a way to reduce mission costs, by minimizing ground processing preparation work and specialized operations teams required at the launch site. However, reliability and mission success cannot be compromised when implementing such an approach. Regardless of mission objectives, it is consistently less costly to identify and correct problems on the ground than in space.

The scope of this technology area includes: transportation of hardware to the launch site; supply chain management; assembly, integration, and processing of the launch vehicle, spacecraft, and payload hardware at the launch site; transportation to and operations at the launch pad; launch processing infrastructure and its ability to support future operations; range, personnel, and facility safety capabilities; launch weather; environmental impact mitigations for ground and launch operations; launch control center operations and infrastructure; mission integration and planning; mission training for both ground and flight crew personnel; mission control center operations and infrastructure; telemetry and command processing and archiving; and recovery operations for flight crews, flight hardware, and returned samples.

Figure 1 summarizes the Technology Area Breakdown Structure (TABS) for Ground and Launch Systems Processing.

The items on the high-level GLSP roadmap, shown in Figure 2, represent ideas and needs based on today's knowledge. As associated technological advancements are realized, and new challenges, capabilities, and customers are identified, this roadmap will adapt accordingly.

Top challenges include overcoming high operations costs, moving away from vehicle-unique infrastructure and launch support systems, addressing the limited integrated demonstration capability for ground and launch systems, overcoming restrictive launch facilities and range capabilities, managing the risk tradeoff for infusing and adopting new technologies, minimizing environmental impacts from launch processing operations, and the need to migrate Mission Control Center functions to automated on-board systems. While existing examples of promising prototype or pathfinder capabilities that can impact GLSP are evident from Industry or other Governmental agencies, technology development is still needed to bring these current capabilities into the NASA environment (for example, offshore floating launch platform).

The "highest priority" technologies identified by this roadmap include (1) low-loss cryogenic storage and transfer, (2) corrosion detection/prevention, (3) autonomous systems and integrated vehicle health management (IVHM), (4) intelligent, self-healing systems, and (5) multipurpose models enabling distributed control and collaboration. National benefits from the investments identified in this roadmap report can be realized in energy conserva-

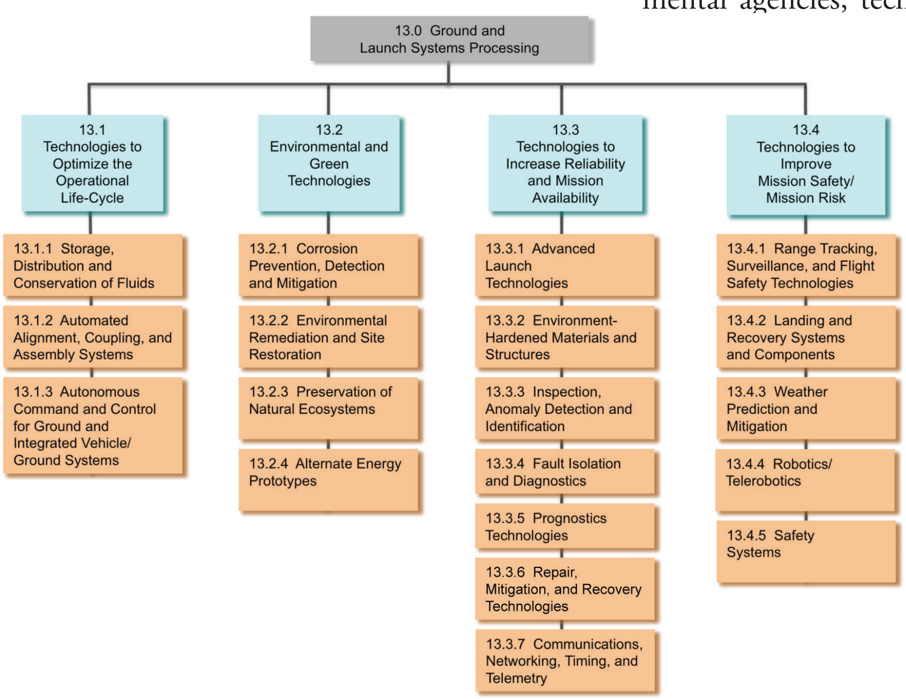


Figure 1. *Ground and Launch Systems Processing Technology Area Breakdown Structure (TABS)*

tion, advanced software and autonomous systems, power generation, storage, and usage, reduced carbon emissions, environmental remediation, corrosion detection and mitigation, low-loss pipelines/fluid transfer, material insulation, weather effects detection and mitigation, and self-diagnosing/self-healing components and systems. NASA needs to invest in innovative technologies to replace the current resource intensive, site specific, systems and processes. These innovations must enable flexible, dynamic, distributed, site-independent, autonomous, accurate ground testing and verification of payloads/spacecraft to enable launch/mission success.

Technologies to implement the "ship and shoot" approach without compromising mission success are only part of the equation. Technologies to transform the systems and processes for "ship and shoot" are also required. In the "ship" potion of this approach, "ship" innovations focus on new means of transportation, handling and assembly of launch vehicles and spacecraft, and the ability to share design, configuration and logistical data between factory, suppliers and launch site. "Shoot" innovations refer to the ability to understand risk posture, improve training and situational awareness, dramatically lower consumables usage and preventative maintenance, minimize launch commit criteria and their ability to impact a mission, and allow for simultaneous missions and for quick turnaround between missions. Technological innovations to enable portable, flexible, distributed, site-independent ground and launch systems processing, while ensuring safety, reliability, and mission success will enable NASA to accomplish more robust space exploration goals. Additional detail on this roadmap is available upon request to NASA.

1. GENERAL OVERVIEW

1.1. Technical Approach

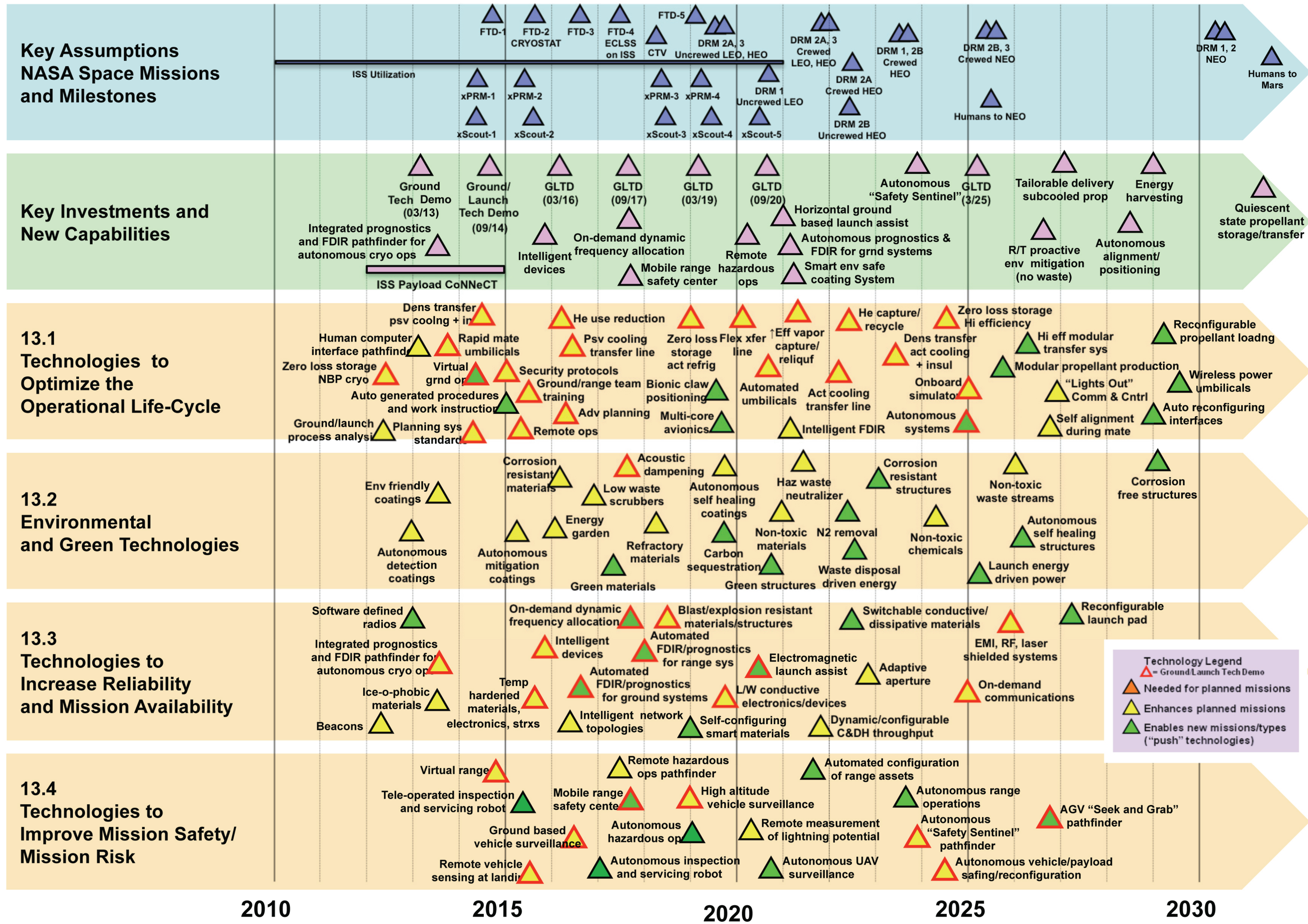
The GSLP technology area team employed a systems engineering approach to roadmap development. Overall goals, processes and major functions associated with ground and launch systems processing were reviewed and decomposed to the constituent systems, subsystems and key technologies. New technologies or improvements to existing technologies and capabilities were identified with commonality, interoperability and systems integration in mind. Standards and architectures to integrate capabilities and migration paths for maturing and validating new technologies were also included.

Successful ground and launch systems processing is a significant contributing factor to the high rate of success associated with NASA's space missions. In order to increase the launch rate and customer base, and provide the flexibility required to completely open the gateways of space exploration, NASA must invest in technologies that eliminate the constraints posed by today's geographically limited, vehicle-unique U.S. launch infrastructure. Technology innovations must enable support for an increasingly diverse fleet of launch vehicles and payloads to be launched from various launch sites destined for various orbits and purposes, while safely meeting the demands for increased launch rates. New technologies must enable flexibility, adaptability, portability, responsiveness, and reconfigurability, without compromising the reliability and accuracy required in GLSP tasks.

A transformational vision for GLSP spans a timeframe beginning with today's Space Shuttle and expendable launch vehicle systems and arriving at a robust space exploration era that is fully able to meet NASA and non-NASA objectives. The concept charts a path to eventually having routine access to space for exploration and commercial operations, and emerging markets that can survive/thrive once the benefits of "micro-gravity" as a tool for research are well understood (e.g., using micro-gravity to gain clearer insights into the unique gene expression afforded in space can enable better understanding of ways to develop targeted pharmaceuticals). The path spans three conceptual timeframes, depicted as "eras" in Figure 3.

The first, or current, era is characterized by transformation, referring to the development of advanced technologies that will make possible new concepts of operation for commercial suborbital and orbital space flights and NASA technology demonstrations in preparation for future exploration. The ground and launch systems technologies developed in this era will initiate a fundamental shift away from vehicle-unique infrastructure, establishing a sustained technology development path to support future missions and space transportation businesses. The broad technology advancements in this timeframe include innovative propellant storage, transfer, and loading; smart sensor technologies; service oriented, adaptable software systems to integrate varied planning and work execution steps occurring at multiple work sites; portable cleaning and in-situ sampling required to service flight and ground hardware with

Figure 2: *Ground and Launch Systems Processing Technology Area Strategic Roadmap (TASR)*



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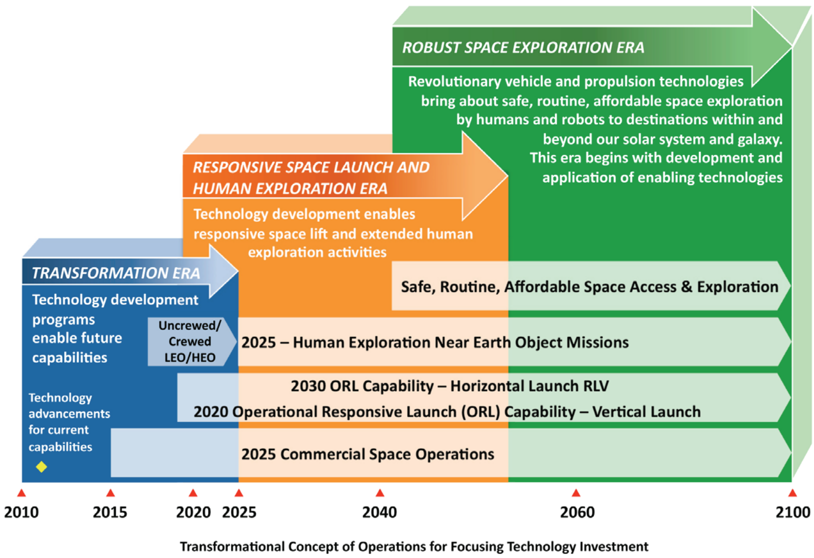

Figure 3. *Transformational Concept of Operations for Focusing Technology Investment*

required commodities (hazardous and nonhazardous); interoperable, advanced command and control; compressed data streams providing for efficient use of bandwidth; and enhanced weather instrumentation for precision forecasting.

Building upon the transformation brought by the new ground and launch technologies, the Responsive Space Launch and Human Exploration Era would begin within the next decade, with activities ramping up in an overlap with the current era. Future missions will be accomplished through the new crew exploration, heavy-lift, and operationally responsive launch vehicle development efforts that began during the previous era. Technology advancements in this timeframe include self-diagnostic integrated health management and healing technologies for ground and flight systems; space-based and unmanned airborne mobile range system platforms; advanced network and data-handling and security technologies; autonomous vehicle and payload servicing systems; close proximity infrared and spread spectrum wireless interfaces; rapid-prototyping, autonomous operations modeling and simulation; flexible, automated vehicle and payload handling, assembly, and integration systems; and two-dimensional and 3-D virtual environment displays.

Safe, routine, affordable space exploration by humans and robots to destinations within and beyond our solar system is characteristic of the Robust Space Exploration era. It is anticipated that, in this era, space transportation will include vital capabilities which are visionary and revolutionary in terms of their significant improvement in the ability of future generations to explore space, and reap the associated societal benefits. The concepts for transforming operations to support this vision are based on rapid planning and execution of flights, shared infrastructure that is adaptable to new missions, standardized interfaces for streamlined operations, multiple simultaneous flights, and minimization of rigid infrastructures. Revolutionary advancements in technology are needed to support on-demand autonomous operations with minimal facility-to-vehicle interfaces, "morphing" and reconfigurable launch facilities, global "space traffic control" range operations, distributed command and control architecture, and energy-harvesting operations (with no environmental impact or waste).

A key aspect of advancing GLSP technologies lies in understanding and appropriately using Integration Readiness Levels (IRLs) to advance System Readiness Levels (SRLs), and intentionally maturing technologies through the Technology Readiness) Level (TRL) hierarchy into operational systems.

1.2. Benefits

GLSP innovations can harness technology advances to increase the reach, reduce the risks, and reduce the costs of NASA missions. An investment in technology to realize substantial cost reductions in ground and launch systems will enable technology development initiatives to be continued concurrent with operational launch programs.

Many key science and technology activities for GLSP can help the U.S. achieve its national priorities in energy conservation; improving healthcare; protecting our national interests; improving and protecting our information, communication, and transportation infrastructure; and strengthening science, technology, engineering, and mathematics education. Many of the areas proposed for research and development in the GLSP Technology Area can have far-reaching commercial applications, which can ultimately lead to new product development. Examples of new products that can transform the deteriorating transportation infrastructure include smart, environmentally friendly, self healing corrosion coating/paint systems for automobiles, highway bridges, gas and liquid transmission pipelines, ships and ports (piers and docks, bulkheads and retraining walls, mooring structures, and navigational aids), railroads and electrified rail systems; and smart, self healing wire insulation and fault detection system to revolutionize aging wiring in commercial and military aircraft. Technologies to address potentially unsafe environmental concerns, including hazardous waste streams and groundwater contamination, can produce new systems for power plant emission control and contamination clean up from gas stations, dry cleaning operations, and chemical manufacturers, respectively. More specific GLSP technologies with high commercialization potential are discussed throughout Sections 2 and 4.

1.3. Applicability/Traceability to NASA Strategic Goals, AMPM, DRMs, DRAs

1.3.1. National Space Policy

The newly released National Space Policy states, "The United States will advance a bold new approach to space exploration," and that "Space operations should be conducted in ways that emphasize openness and transparency to improve public awareness of the activities of government, and enable others to share in the benefits provided by the use of space." By optimizing the operational life cycle, creating environmental technologies, improving launch availability, and enhancing mission safety and risk postures, NASA's investment in GSLP technologies will enable robust, innovative, responsive, transformational, and cost-effective access to space.

1.3.2. Agency Mission Planning Manifest (AMPM)

From a mission "pull" (enhancing planned missions) perspective, all of the flights identified on the Agency's manifest contain the requirement for space flight hardware to be integrated, processed, and launched into space, and operated once there. Enhanced capabilities realized by incorporating new ground and launch technologies, such as data interoperability, increases in launch availability, autonomous operations, and improved situational awareness, will reduce the potential for cost overruns and schedule delays. Investments in these enabling technologies will be based upon need, the ability to make the biggest improvement in mission capabilities, and their benefits to a program's operational life cycle.

1.3.3. Ground Launch Technology Demonstrations (GLTD)

From a mission "push" (enabling new missions/types) perspective, a series of GLTDs will be required to integrate and test a bundled set of technology capabilities (i.e., a "reference" architecture) into an operationally relevant environment. The GLTD concept allows for integration between the technology programs, test flight/flagship demonstration programs, and the operational programs to prove and mature the technologies that would most improve the nation's access to space. A GLTD should be viewed not as a single event at a single location, but as a "campaign" of related technology demonstration objectives that can occur across the nation, tapping into testing capabilities and support systems across NASA, the federal government, and industry. For example, an early GLTD could include the following candidate component technologies: highly efficient cryogenic storage and transfer using advanced insulation technologies; propellant conditioning using compact heat exchangers to improve propellant quality at the vehicle interface; reduction in helium use by using advanced sensors for real-time in-situ measurements to reduce/eliminate overpurging practices; geographically distributed, advanced command and control architectures; integrated system health management/fault detection, isolation, and recovery; and corrosion-prevention materials. GLTDs would showcase a distributed demonstration "network" (e.g., vehicle providers, commercial data centers, test stands, and control rooms distributed across NASA Centers).

Regularly scheduled technology demonstrations (approximately every 18 months) would provide the means for technologists, engineers, and operations experts to collaborate in fielding demonstrations for advancing the TRL and IRL of component technologies. Promising technologies that are proven via GLTD could then be incorporated into test flights, referenced for the planning of future missions, or retrofitted into upgrades of existing operational capabilities.

1.3.4. Driving Requirements

The driving requirements of the GLSP Technology Area are quite simple, as resources saved on the recurring ground costs can be then applied to new missions, more frequent missions, and increased access to space. While GLSP is clearly tied to and highly dependent upon launch vehicle design and servicing requirements, cost reductions can be realized with smaller operations teams by using technologies that incorporate materials and systems to reduce recurring maintenance and servicing requirements; autonomous support systems to streamline operations, reduce error, data integration, and rework; and multiuse, multicustomer capabilities to allow for sharing of infrastructure costs. It remains essential, to the greatest extent possible, that ground and launch systems technologies are jointly developed with launch vehicle developers.

The ratio of direct, ground-specific operations costs to total program costs provides a ground operations cost ratio (GOCR), which can be used to gauge the transformation of GLSP capabilities. While there are wide fluctuations across the nation's space ventures (human, robotic, and commercial), the aggregate GOCR for 2010 is estimated to be roughly 40%; that is, 2 dollars out of every 5 dollars are spent on maintaining infrastructure as opposed to directly supporting space missions. This assessment comes from a review of the FY07 to FY10 Space Shuttle Program Budget[1] and a study commissioned by the Launch Services Program[2]. A separate 2008 economic analysis developed by the Massachusetts Institute of Technology indicates that an aggregate of 16% of every dollar spent by U.S. consumers on airline travel goes into airport services, support infrastructure, and security[3]. While this represents a stable, long-term capability with heavily used aircraft, the 16% figure is a challenging but reasonable goal for the future infrastructure costs required for accessing space.

The ability to eliminate prerequisite operations; increase insight into the configuration, state, and health of the launch vehicle/ spacecraft/payload and supporting systems; the reduction of unique, single-point failures that impact mission success; the ability to "virtually" qualify a space mission; and reducing the potential for weather and range conditions to impact a mission, will increase launch availability. Several factors go into launch availability, but the basic measurement is a ratio of "up time" (mean time between failures, system readiness, etc.) compared to "down time" (mean time to repair, preventative maintenance, certification, weather, logistical and administrative delays). Based on a 2008 study performed for the Shuttle and Launch Services Programs, the launch availability rate of the Space Shuttle Transportation System was roughly 54%, and the Delta II was approximately 56%, while the stated goal of the Constellation Program was 99% availability. Performance data for the airline industry on flight availability (i.e., flight not being cancelled) is 98.5% for the year-long period ending August 31, 2010.[4]

In the environmental management arena, the reduction in the usage of nationally strategic materials and toxic/hazardous materials is an important goal to move toward proactive real-time environmental mitigation (no waste). As an example, the Shuttle Program current usage of helium has been 40 million standard cubic feet (scf) per year for all operations including launch and ground processing, while the Constellation Program predicted usage was 52.8 million scf per year, with a technology development performance goal to reduce overall helium usage to levels 50% less than the vehicle engine design point by 2015. Specific examples of potential technologies are provided in Section 2. Corresponding Figures of Merit are provided as follows:

1. Reduce fixed costs required to maintain space launch/operations capabilities
   - Figures of Merit Goals:
     - » **FY16:** Aggregate Ground Operations Cost Ratio (GOCR) is 35%
     - » **FY21:** Aggregate GOCR is 25%
     - » **FY31:** Aggregate GOCR is 16%
2. Increase launch and landing/recovery availability (capability to initiate and/or conclude a mission)
   - Figures of Merit Goals:
     - » **FY16:** 70% availability (256 days per year)
     - » **FY21:** 80% availability (292 days per year)
     - » **FY31:** 95% availability (347 days per year)
3. Improved management of environmental resources
   - Figures of Merit Goals:
     - » **FY21:** 66% reduction in usage of nationally strategic material (e.g., helium and titanium) by the nation's space program; 50% reduction in usage of toxic products
     - » **FY31:** 90% reduction in usage of nationally strategic material by the nation's space program; 75% reduction in usage of toxic products; facilitate the creation of at least one completely "green program" with zero toxins for vehicle, propulsion, commodities, or infrastructure

1 *http://www.nasa.gov/pdf/383305main_CostEstimates_SDHLV_Rev1.pdf*

2 *http://ceg.files.cms-plus.com/PruneJobsRelevantNAPAPublications/NASA--LaunchServicesProgram(%2335).pdf*

3 *http://web.mit.edu/airlines/analysis/analysis_airline_industry.html*

4 *http://www.bts.gov/programs/airline_information/airline_ontime_tables/2010_08/html/table_01.html*

1.4. Top Technical Challenges

1.4.1. Resource Intensive Processes for Ground and Launch Operations

Today, space access is time-consuming, expensive, and not reliable enough to enable robust space exploration. The expense is largely due to the resource-intensive processes required to prepare the vehicle and payload for its mission. Technology solutions/innovations are needed to enable processes that are flexible, adaptable, portable, distributed, and site-independent.

1.4.2. Vehicle-Unique Infrastructure and Launch Support Systems

Emerging vehicle architectures pose a special challenge for ground and launch processing because unique facilities, systems, and equipment have always been required for each vehicle type. Examples include specialized systems for hypergolic propellant servicing and ammonia cooling, very sensitive detectors requiring special purges and protective covers, radioisotope thermoelectric generator (RTG) power systems, specific T-0 interfaces, payload unique commodities for purge or dewars (argon, Xenon, cryogenic fluids), unique GSE handling interfaces (slings, spreader bar), special purge carts, program-specific data architectures, and security for RTG systems. Program-unique or vehicle-unique assets tend to become legacy assets because cash-strapped programs can generally only afford operations and maintenance of existing assets rather than replacement or large-scale modernization. Technological obsolescence increases as the pool of legacy assets grows, resulting in proliferation of assets that are expensive to operate and maintain because they cannot employ new technology.

1.4.3. Limited Demonstration Capability for Ground and Launch Systems Technologies

The existing ground and launch infrastructure consists of a collection of recent, dated, and obsolete technologies that have been proven to fulfill mission needs. Emerging technologies have a large (often insurmountable) hurdle to prove their ability to exceed existing functionality, "not preclude" current operations, and provide tangible benefits. Human-rated and flight-certified systems are currently not available for testing or implementing promising new technologies. To take maximum advantage of a new technology and its potential to reinvent ground and launch processing with radically new concepts of operations, the ability to "prove" technology advances on a scale and environment that reduces risk to an acceptable (engineering) level is necessary for infusing technology advances into ground/vehicle system designs. A reference architecture, or a suite of them, is needed to enable technology demonstrations for the purposes of intentionally maturating emerging technologies for GLSP operations from concept to usage. GLSP technology demonstrations must implement large-scale testing and evaluation to prove the systems work in "real" applications.

1.4.4. Restrictive Launch Facilities and Range Capabilities

The GLSP requirements for current space vehicles, both expendable launch vehicles (ELVs) and reusable launch vehicles (RLVs), have led to some very restrictive launch facilities and range capabilities. Some of the key limiting factors dictating launch site locations, such as orbital destination of a payload and the population of areas under the launch trajectory path, will not be altered by technology innovations in GLSP. However, innovations that introduce portability, flexibility, quick reconfigurability, eliminate dependence on facilities with specific capabilities, and check-out systems and services that can accommodate a variety of vehicles, payloads, commodities and interfaces, can expand space exploration and enable a network of spaceports. Because the launch and ascent phase of test vehicles poses a threat to safety of people and property, such vehicles are only allowed to fly from test ranges or restricted launch centers with flight termination systems ready to destroy the vehicle and its payload if it diverges from the intended flight path. Use of test ranges restricts launch sites to only a handful of facilities worldwide. Innovations to enable tracking and control of a launch vehicle without expensive ground assets, such as space based range, onboard tracking systems and autonomous flight safety systems, will reduce the barriers associated with traditional range restrictions. Having transportation infrastructure to receive and send everything necessary for a mission, whether by ship, rail, roadway, or aircraft, is also another limiting factor to establishing a network of fully functioning spaceports. As larger payload fairings become available on more launch vehicles such as 5 meter, 7 meter, and perhaps 10 meter, transportation limitations on height and width due to airplane size, roadway restrictions, and rail freight car width allowance will become more problematic. Ocean transportation is an alternative, but it can take much more time and can be at risk due to weather (storms, tropical weather disturbances, ice in waterways). These issues are traditionally addressed by road (widening, leveling) or utility (power, streetlight, stoplight, etc.) modifications and altering the transportation route, but they could also be addressed with innovative transportation options such as larger aircraft, dirigibles, or other alternatives. Pathfinder transportation technologies developed by the other federal agencies, the marine industry, and Aeronautics Research Mission Directorate can be used for these NASA applications.

1.4.5. Risk Tradeoff for Infusing and Adopting New Technologies

As we enter a new, transformational era in our nation's space program, this is not a time to be conservative in our approach to adopting new technologies for improving access to space. The risks inherent in inserting new, sufficiently mature ground and launch processing technologies into current operations and new missions will need to be analyzed, understood, and appropriately mitigated or accepted. To maintain the appropriate safety and risk posture for operations personnel, customers, the general public, as well as launch vehicle, spacecraft, payloads, and supporting systems, future GLSP capabilities will require a balanced approach that includes new technologies to provide Safety and Mission Assurance (S&MA) personnel better insight and understanding into system configuration, risk tradeoffs, and the ability to trend and predict failures and operational hazards, and enable innovative concepts for performing critical S&MA tasks.

1.4.6. Environmental Impacts from Launch Processing Operations

GLSP activities have the potential to introduce environmental impacts to a variety of launch complex assets and surrounding launch site ecosystems. Problems with infrastructure deterioration, acoustics, groundwater/runoff, contamination control, waste disposal, nature preservation, and conservation/resource management can be addressed with technology innovations to assess and remediate, or eliminate, these impacts.

1.4.7. Migration of Mission Control Center Functions to Automated Onboard Systems

Today, most mission planning, training, and real-time systems monitoring is done by teams of mission planners, flight controllers, and instructors over many months before and during the missions. Limited computing power in onboard systems restricts the quantity of these functions that can be performed; but as computing and database technologies advance, the flight systems will become more capable, allowing many planning and mission control functions to be automated and placed in onboard systems. As examples, if the crew needs to postpone a task, the onboard system would automatically re-plan the activity at a future time while meeting all the constraints for the task. Likewise virtual training models and scenarios would be stored onboard, allowing the crew to do training closer to the actual event than allowed today on long duration missions.

2. DETAIL PORTFOLIO DISCUSSION

2.1. Technologies to Optimize the Operational Life Cycle

Optimizing operational life cycles is the most direct way to decrease costs and increase efficiencies to provide more launch opportunities for government and commercial industries. Because the cost of ground and launch processing operations represents a large portion of the total mission cost, GLSP technologies that provide a small increase in effectiveness can produce a huge cost savings. These technology developments will also significantly improve overall ground safety by reducing the hazard level of specific operations and reducing the number of operations required to be performed. To process new space launch vehicles, the nation needs systems that will function more independently, require less maintenance, and use new instrumentation technologies.

Current ground operations are designed primarily around the processing, launch, landing and recovery of the launch vehicle architecture. Time and cost efficiencies may be possible to achieve by streamlining, optimizing or re-engineering existing processes or optimizing the use of materials and commodities. Tools and methods for analysis of processes and tasks exist today and have been used in studies associated with payload processing operations related to late stowage and use of the micro-science glovebox. An analysis of ground operations processes will be conducted to identify bottlenecks, redundant steps or suboptimal processes that can be eliminated, improved or optimized.

Once ground and launch operations processes are analyzed, 3-D simulations will be created of the processes, and human-performance models will be created to capture the human's role in TA-13 operations processes. Together, models and process simulations will form the basis of a "virtual ground" environment, which will be used to simulate and assess the functions and interactions of the ground and launch crews. The virtual ground environment and the virtual range environment will allow program planners and systems designers to visualize and assess processes and procedures, identify and mitigate potential safety hazards, and plan hazardous operations. Opportunities will be identified to improve or optimize individual and team performance and increase productivity. Simulations will enable integrated planning and assessment of skills and other resources to support ground and launch operations. Simulations will also used to support virtual ground and launch crew training.

A pathfinder will be conducted to investigate and deploy human-computer interface (HCI) technologies and approaches such as 3-D heads-up displays, mobile computing, augmented reality, natural language processing, virtual control, voice-activated commanding, and other interface technologies. HCI technologies developed in TA-4 (Robotics, Telerobotics, and Autonomous Systems) and TA-11 (Modeling, Simulation, Information Technology, and Processing) and will also be leveraged within ground and launch operations. A pathfinder for automated generation of work instructions and procedures and identification and mitigation of safety hazards will be developed, ending the reliance on costly manual processes to execute these functions. These pathfinders will be leveraged with other pathfinders identified in TA-13 to investigate methods to improve service delivery and assist ground, launch, and range personnel in tasks such as maintenance, inspection, guided-troubleshooting and repair, monitoring, and diagnosis.

Virtual ground and range capabilities will provide robust, high-fidelity, on-demand training to the launch and range team to ensure the workforce skills are developed and maintained; such training is difficult to acquire today because the same resources used to deliver the training are also used to process and launch the integrated launch vehicle/payload/spacecraft system. The net effect will be an improvement in situation awareness, safer operations, and a reduction in the workforce requirements and cost for ground and launch operations.

2.1.1. Storage, Distribution, and Conservation of Fluids (Cryogens, Liquids, Gases)

Current-day propellant servicing operations are hazardous, and controlling the associated hazards is time-consuming. Although computer systems control these servicing operations, a large workforce is required to monitor propellant-loading operations to maintain the safety of the vehicle, payload, and crew. Engineers evaluate the performance of ground and flight systems as well as monitor for hazardous conditions that can quickly propagate into loss-of-vehicle conditions. Because of the hazardous nature of these systems, maintenance and servicing require significant diligence. These restrictions do not allow for rapid propellant-servicing operations and impose additional maintenance requirements for support equipment. Current cryogenic storage and transfer systems are plagued by thermal inefficiencies that increase vehicle safety risk, drive costly commodity boiloff losses, and limit the distance over which these commodities can be transferred.

To achieve the 20-year vision for quiescent-state storage and transfer of cryogenic propellants used in vehicle-servicing processes (i.e., a water-like flow, without the problems associated with using pumps or pressurization issues for controlling the flow), technology investments need to be made in the control and manipulation of the thermodynamic conditions of the cryogenic fluids. Technologies for optimizing life-cycle costs include on-demand fluid production; high-efficiency and configurable propellant storage, transfer and, recovery systems; conservation of critical, expensive resources; and active/passive thermal control of the fluids themselves at critical points in the fluid-servicing process.

For storage systems, mission pull technologies include:

- Near-term development of storage tank insulation materials that provide a 40% reduction in convective/radiative heat transfer (e.g., aerogels, polyamides, glass bubbles, multilayer insulation, and composite systems that are resistant to moisture, UV exposure, or mechanical damage) and zero-loss storage of normal boiling point (NBP) cryogens (e.g., cryogenic hydrogen storage in composites).
- Midterm development of storage tank insulation materials and structures that provide a 25% reduction in conductive heat transfer (e.g., load-supporting multilayered insulation to eliminate heat leak from the storage tank

supports/penetrations) and zero-loss storage using active refrigeration (cryocoolers).

- Far-term development of storage tank insulation materials that provide a 50% reduction in conductive heat transfer (e.g., insulation for complicated tank shapes to replace foam, with less mass) and high-efficiency zero-loss storage using active refrigeration.

Mission push technologies include development of supercooled solid propellant storage for transfer to smaller-volume flight "tanks," super pressure vessels for closer-to-room-temperature fluid storage, super light weight propellant tanks using aerogel composite fibers (using 3-D composite machine to filament wind these fibers around a thin core) with decreased weight and improved thermal conductivity, and modular storage tanks with lightweight noncompacting insulation and closed-cell hybrid microfoams to support flexible operations.

For transfer systems, mission pull technologies include:

- Near-term development of high-efficiency flexible transfer lines with a bend radius < 20°, high-efficiency transfer line couplings, and passive vacuum and better materials for ground-based vacuum-jacketed systems.
- Midterm development of high-efficiency flexible transfer lines with bend radius < 10°, passive cooling for transfer lines to save 50% in transfer losses, low-maintenance insulation materials to overcome conductive heat loss in transfer, load-supporting pipeline insulation, and long-distance, high-efficiency transfer lines with vapor shielding.
- Far-term development of high-efficiency flexible transfer lines with a bend radius < 5° and active cooling for transfer lines (zero-loss transfer).

Mission push technologies include development of reconfigurable materials and composites for thermo-mechanical multifunctionality fluid systems (e.g., aerogels and polyimide/aerogel foam composites to replace vacuum-jacketed piping, switchable active insulative/conductive materials for combined heating and cooling, and passive-acting materials with insulative and conductive elements that provide uniform heat flux), permanently chilled transfer lines and flexhoses/flexipipe, and modular transfer systems to support flexible operations.

For high-efficiency recovery, purification, and reliquefaction systems, mission pull technologies include:

- Near-term development of an integrated refrigeration and storage system for liquefaction.
- Midterm development of nonhazardous and environmentally friendly high-efficiency vapor capture/ reliquefaction systems.
- Far-term development of zero-waste product scrubbers.

Mission push technologies also include development of materials and systems for hypergolic fuels degradation and production of usable commodities from the waste stream.

Large-volume consumption of helium (He) remains common practice for in launch processing of vehicles that use liquid hydrogen (LH_2)/liquid oxygen (LOX) engines. Because He is a nonrenewable, finite resource, this unbridled use threatens its availability for use by future generations. For prelaunch operations, sensing is required prior to introduction of both LH_2 and LOX to verify that all the condensable gases have been removed from the feed line. For postlaunch operations, sensing is required for safing the LH_2 system after launch or scrub turnaround to verify the line is inerted and no hydrogen remains. Samples are extracted from a transfer line and sent to a lab for analysis, a time-consuming process that occurs during time-critical operations such as launch countdown or scrub operations. The current He purging philosophy is very conservative, using high flows and long flow times, to mitigate significant delays that could occur if the first samples taken for analysis fail the system purity requirements. The concept of operations for He purge of LH_2/LOX engine systems is expected to remain as current practice until technologies are developed for new launch propulsion systems. Development of ground fluid systems to support new liquid engine system concepts, including high specific impulse LOX/LH_2, high energy density kerosene, and alternative hydrocarbon (LOX/methane) based engines, will be coordinated with TA-1 (Launch Propulsion Systems).

To conserve He, sensing technologies are needed to reduce/eliminate overpurging practices, purges need to be made more effective, and new systems are needed for capture, storage, and purification of He. Mission pull technologies include:

- Near-term development for reducing He use: Technologies for real-time in-situ measurement would allow using only the minimum amount of He needed to meet the engine specifications. These include nonintrusive flow meters, wide area sensors, and point sensors for gaseous hydrogen, water vapor, and gaseous oxygen detection. For a specific operation (LH_2

line purge), a savings of at least 30% over current Space Shuttle use is anticipated with implementation of sensors that can provide real-time purity analysis.

- Midterm development for eliminating He use: He purges are currently used because of concerns about the solubility of nitrogen in oxygen, which would affect engine performance, and nitrogen condensing in hydrogen, which could cause engine damage. Alternative technologies to minimize/eliminate helium purges include low trapped volume valves/components to enable use of gaseous nitrogen and gaseous hydrogen purge sequencing, new types of insulation to eliminate umbilical plate cavities requiring helium purges, in-situ measurements in transport systems with minimal protrusion and trapped gas volumes, and molecular trap devices to keep condensable gas contaminants from reaching critical propulsion components.
- Far-term development for He capture, storage, and recycling systems: Technologies are needed to recapture vented He from tanks and purges and store large He volumes created during high-flow-rate purge operations (e.g., inflatable storage), directly recycle pure waste streams (e.g., small, high-efficiency compressors and He regulation/distribution/in-situ purity verification systems), and economically purify/reclaim high-volume, high-quality waste streams in real time (e.g., membrane/catalytic separators to remove nitrogen and hydrogen gas contaminants, intermediate stage purifiers, and liquefaction and recompression systems).

Space flight vehicles use high-energy, volatile fuels. To achieve the capability for autonomous propellant loading and tailorable delivery of sub-cooled (densified) cryogenic propellants at the vehicle interface by 2030, investments in technology need to be made to enable high-efficiency propellant production, loading, servicing, and conditioning systems. Mission pull technologies include:

- Near-term development of compact heat exchangers (e.g., passive Joule Thomson expansion with expanded foam heat exchanger and inert fluid) for end point/vehicle-interface conditioning of the fluid stream (efficiency, E), passive cooling systems for densified transfer with low-maintenance insulation systems, automatic deicing/ contamination/ dust removal quick disconnects (QD) (see Figure 4), electro-magnetically actuated valves to reduce parts count and system complexity, cryogenic piezoelectric actuators to minimize heat input to the fluid, and small, magnetically coupled seal-less cryogenic pumps.

Figure 4. *Ice contamination on QD sealing surfaces*

- Midterm development of compact heat exchangers for end-point active conditioning of fluid stream (E = 20% improvement over near-term solution), active cooling systems for densified storage and delivery with improved insulation, insulation system for cavities such as umbilical disconnects and flange joints, compact stemless valves, leak-free cryogenic fluid valves, and large cryogenic pumps (without the use of dynamic shaft seals) to minimize or eliminate hazardous operations for real-time repairs, and highly efficient, and environmentally friendly propellant production systems.
- Far-term development of compact heat exchangers with tailorable delivery parameters below normal boiling point conditions, active cooling systems for densified transfer with improved insulation, self-sealing/self-cleaning cryogenic QDs, and modular/responsive propellant production systems.

Mission push technologies include development of flexible, lightweight materials/composites for reduced numbers of components, activator/deactivator chemical/electrical agents to enable/disable propellant combustibility, fuel deservicing neutralizers, rapidly reconfigurable propellant loading systems, and high efficiency, low-cost alternatives to cryogenic fluid production (e.g., thermochemical splitting or nuclear-powered, high-temperature electrolysis for hydrogen production in lieu of conventional steam methane reformation).

A 20-year life-cycle cost analysis performed in October 2009 detailed $335M in cost savings with investment in cryogenic fluid management (CFM) technologies for zero-loss storage and transfer, long-distance high-efficiency transfer, fluid conditioning, advanced insulation systems, and leak detection instrumentation, and $100M in cost savings with investment in He consumption-reduction technologies. Other figures of merit related to improvements for risk/safety and reliability/maintainability/operability, cost assumptions, and rough order of magnitude (ROM) estimates for ground systems implementation costs supporting this return on investment (ROI) analysis are available upon request to NASA. There is high confidence that the mission push technologies will be achievable within the stated timeframes because both the CFM and He reduction technology tasks were formulated under the Exploration Technology Development Program (ETDP).

2.1.2. Automated Alignment, Coupling, and Assembly Systems

Flight hardware assembly operations today are slow because of the complex positioning, rotating, and lowering of the flight elements. These operations require highly skilled crane operators who can perform intricate maneuvers in both speed and position. In addition to the crane operators, human "spotters" are required to verify proper clearances between the flight hardware and any obstructions. Final assembly and closeout of the interfaces also tends to be labor-intensive, requiring special skills because of the complexity of the unique interfaces that each payload or vehicle uses for movement and assembly as well as the intricate positioning, rotation, and handling of fragile pieces and the handling of toxic and hazardous commodities.

Previous programs have devoted significant time and money to transportation, alignment, connection, and interface testing during critical-path operations. Technologies must be developed to enable expedited movement, precision positioning, and assembly of flight and payload elements while ensuring the safety of the workforce and hardware, minimizing the human interfaces, unique transportation, handling, and assembly ground support equipment (GSE), and manual and hazardous operations required. Enabling technologies include advanced mobility, enhanced sensing and alignment, self-guiding and self-positioning systems; autonomous interface systems for rapid flight element integration; and robotic support for handling operations. It is vital that the ground and launch systems technologies are jointly developed with launch vehicle system developers because the interfaces need to be robust enough to accept forces from the handling, alignment, and assembly systems.

Handling fixtures today are composed of heavy steel beams or slings with little sophistication. But with advanced sensing technologies, such fixtures could self-adjust based on the load. An example of such a system would be a variable-center-of-gravity beam that automatically adjusts to maintain the proper center of gravity during the lifting operation. Development of onboard laser tracking systems for the vehicles/payloads being processed, when coupled with a rail system, can eliminate dangerous crane operations. The system and technology can be designed to fully automate any ground processing maneuver to condense processing time and improve safety and efficiency. High-strength materials that do not change their geometric properties through different environments need to be developed as well as pneumatic motors to control massive vehicles to the accuracy needed to mate these bodies. Other technologies for development in the near-term to midterm include high-capacity air bearings with real-time feedback systems for precision control and bionic (grappling) claws for offloading and moving parts or spacecraft. Development of automated lifting, handling, and assembly devices (robotics) could include magnetism technologies for assembly and transportation, automated "clamping" devices so cranes/equipment can hook up to GSE/lifting slings in minimal time, and autonomous self-propelled robotic movers for hardware transfer. Development of molecular sealant attachment devices and electromagnetically levitated payloads are far-reaching technology concepts for transportation and handling.

High-accuracy positioning and alignment systems require development of real-time, rapid, and quantifiable measurement system technologies. These technologies include vision-based alignment and positioning, GPS alignment with high-accuracy triangulation, high-accuracy laser guidance, and optical and non-optical positioning systems. Self-aligning element technologies could include a network of small self-contained but communicative devices that, when attached to stationary (possibly surveyed) locations, and on vehicle, payload, or servicing devices, produces an active, self-calibrating real-time dimensional network. Data from this network would be merged with engineering drawings of facilities, equipment, and vehicle elements to track motions and alignments in real-time to a design precision. This system would support automated stacking/mating, interference (collision) avoidance, and time optimal operations. Autonomous positioning and self-alignment during mating is enabled by far-term technology development of automated control systems for self-positioning and self-configuring, advanced assembly monitoring devices such as artificial vision devices, and self-calibrating positioning systems.

Advances in vehicle interface systems, such as umbilicals, can also significantly reduce operational turnaround times. Technology development in the areas of alignment, mating, and release mechanisms can implement sophisticated connectors that reduce occurrences of misalignment during mate and frangible disconnects, and advanced vision systems that enable reliable, automated mating, disconnect, and reconnect at any point in the countdown process, improving the safety of launch operations. Automated umbilicals will dramatically reduce the time required to mate an umbilical system to the launch vehicle interface. To do so, the ground umbilical plate must have a highly accurate positioning mechanism with an associated control system that will locate the ground umbilical plate with respect to the flight umbilical plate. The umbilical ground plate must be able to track the flight plate in real time as the ground plate is extended out toward the flight plate in the umbilical mate operation, and constantly adjust position even if the flight plate is moving or vibrating. Technologies to enable fully automated, ground-to-vehicle extend-and-retract umbilical systems include an autonomous control system that provides verification of mating integrity, location/alignment systems, latching/ actuation systems, autonomous operation and automated mating, location control and reconnect capability, and ice suppression technology.

Location and alignment system technologies include self-verifying interfaces and non-optical positioning systems (e.g., radar, magnet, sonar) to align to a moving vehicle in order to reconnect the ground-to-flight interface. Latching technologies include shape memory alloys and pneumatic collets, and self-latching mechanisms for high-speed disconnect operations as well as automated mates of T-0 umbilicals. Rise off umbilical interfaces (for fluid, data, and electrical connections), thermal umbilicals (bidirectional), magnetic attach umbilicals, contactless electrical interfaces and umbilicals, automated fluids umbilicals, and radio frequency (RF) ground data umbilicals (except for required fluids and minimal ground electrical power interfaces) should be developed to support autonomous operations. QD fittings, which are mounted onto umbilical systems with related mechanisms, mate or demate the QDs to the launch vehicle ground-to-flight interface. Technologies for quick disconnects including self-sealing, self-verifying, self-cleaning, and automatic deicing and contamination removal ensure safety and reduce the hours expended performing leak checks before each operation. Building on current technology for wireless data transfer, far-reaching technologies for wireless umbilicals include radio frequency optical power transfer and wireless ground power systems to reduce wiring infrastructure life-cycle costs.

Although development of common, standardized ground-to-vehicle, ground-to-payload, and payload-vehicle interfaces (umbilical, electrical, and fluids connections, protocol and data structure schema, equipment, etc.) was generally considered to be an engineering design/ processing improvement, technologies should be developed to facilitate successful interface testing without physical proximity, including modular, wireless, virtual, and auto-reconfiguring interconnect and interface systems for separate elements such as pieces of a payload, payload and launch vehicle, or elements launched separately and mated for the first time in space.

2.1.3. Autonomous Command and Control for Ground Systems and Integrated Vehicle/Ground Systems

As future exploration missions combine human and robotic elements, as well as involve international partners, technologies that allow worldwide access to models and data and command systems will be necessary. As humans travel beyond LEO, new technology must move as much of the planning, training, data monitoring, fault detection, and recovery as possible to onboard systems.

Today, models for development and operations are used at different times and typically involve different levels of functionality. Comprehensive, multiuse/multipurpose models need to be developed for both the development and operations communities for more accurate predictions of activities and execution with little or no modification for specific uses. In addition, hardware-in-the-loop testing is often the "gold standard" today for operational validation. However, hardware is only available near the launch date and is always a limiting resource. High-fidelity software simulation-based testing would support much larger test suites run more frequently without adversely affecting mission budgets and timelines.

While some functions of planning and scheduling systems are automated today, much of this activity is labor-intensive. Advances in computing technology will allow planning and scheduling systems to optimize the use of resources during ground and mission operations, from the execution of daily tasks to working within all constraints and requirements to plan longer-range activities. As schedule changes are applied, areas will be identified where required conditions or resources are not met and schedules will be automatically adjusted, or the best options for meeting the requirements will be recommended. This will reduce the number of planners to only those needed to work these identified disconnects.

In the future, planning systems must include the ability to mine historical data and track current data to accurately represent tasks and events in plans. By integrating the knowledge bases from these areas, the future planning systems will have a "self-learning" capability that will aid in autonomous long-range planning. These systems must be able to generate plans, schedules, procedures, and other mission-related documents. By maintaining a direct link to the latest system changes or updates, launch processing teams will always have the latest information available for real-time execution of work. This will also allow for the transmission and collection of completed work, deviated or deferred work, and anomalous conditions to a database for archiving. These systems must also collect and distribute planning related data across multiple platforms and systems. Future planning and scheduling systems will be linked directly to a supply chain management system that will allow for full life-cycle tracking of products from initial development (schematics, diagrams) through delivery and recent use (stowage locations, consumption status, run times, etc.).

Today training is done at many levels, typically culminating in large and expensive simulators for human space flight programs. Training involves multiple years of generic and mission-specific training for crew members and mission controllers, much of which is concentrated close to the launch date. As human missions become longer, the need for refresher training closer to an actual event will be necessary. As an example, a crew will rendezvous with an asteroid or land on Mars many months after the last time they practiced in a ground-based simulator. As a result, the technology to move simulator-equivalent training to the onboard systems will be needed to allow close-to-the-event training for major events. Major strides have been made in the area of virtual, 3-D modeling and visualization. As this technology continues to advance, the use of 3-D displays and video will greatly improve onboard crew training and real-time operations. This would also provide the opportunity to minimize pre-mission training for less critical events such as maintenance or payload activities. Technologies that provide a natural language/universal translator, heads-up displays, holograms, and voice communication systems will reduce the size of the ground support team needed for training and real-time operations.

While multi-mission control centers are becoming more prevalent today, particularly in the commercial satellite world, much of the launch and mission control center infrastructure in use for human and older scientific NASA missions was developed to support the data architecture of a single mission or multiple missions of a single class. Re-configuring a control center to support a new mission is very labor intensive. Connections to other control centers are typically done by defining unique interfaces for point-to-point data and command transfer. While payload data and commanding is generally distributed to various investigator locations, the command and control functions for the core systems, particularly life support systems in the case of human mission, typically is not. This drives the need to centralize the mission support team into a small number of control centers. To combat this labor intensive centralized approach, distributed service oriented architecture technologies will need to be pursued. Development of an open architecture platform will decouple common information services, models and middleware from applications and improve reuse and interoperability between applications. Shared messaging infrastructures, common data definitions, common meta models and information models constructed through well-defined standard interfaces provide the capabilities required to achieve distributed, optimized, and interconnected control centers that can all support any aspects of mission planning and real-time operations and pass control authority to each other as needed by the mission.

While a ground support mission operations team will always be needed for major activities, the mission control team for long duration missions should be one of pre-mission planning followed by on call support when necessary. While it may be many years before a ground control center can go "lights out" during human missions, smarter ground and onboard systems performing automated fault detection and isolation will enable more of a "duty officer" scenario supplemented by on-call expertise. As multiple and simultaneous missions become a reality, the need for technologies to allow handoffs from one control center to another will also be critical (similar to today's Air Traffic Control systems). While technology will reduce the need for ground personnel to constantly monitor the spacecraft systems health, it will also allow more routine communications to take place between crewmembers and friends and family on the ground. Advances in delay tolerant networks and moving internet protocols to space will allow long duration crewmembers to communicate using many of the tools and social media available to them today from their homes, albeit with a noticeable time delay.

Space-borne computing efficiency may not be viewed as directly linked to ground ops processing, but limitations on flight system computing resources increase the complexity of the ground operations system. Improvements in space-borne computing efficiency would facilitate implementation of onboard autonomy, fault management, sensor fusion, data reduction, and data management, which would then enable commensurate reductions in ground operations. Many current applications are unable to "fly" because the onboard computing capacity to support them does not exist. With the continued maturation and increased capabilities of personal computers and Personal Data Assistant (PDA) technologies, the ability to move the data to the system experts versus needing to move the system experts to the data, becomes feasible. Technologies will be required to allow distribution of real-time data and voice loops to any PC or PDA, allowing all system experts to support when needed regardless of their location.

Likewise, the state of the art in data archival and retrieval systems must be expanded to ensure all testing, simulation, and real time data is seamlessly archived, archives are linked, and all data is easily accessible from any location around the world. One issue that will need to be resolved is the IT security requirements that today throw roadblocks in the ability to distribute data and commanding capability. Explicit methods for secure access of services and exchange of information are required to simplify the overhead currently required to access NASA databases, particularly for internationals who are supposed to be part of future NASA missions. Personal confirmation technology must be developed that allows for easy verification of the individual's identity so they can access the systems they are authorized to access regardless of whether they are accessing it from a control center, their office, a home PC, or their PDA.

Additional, emerging command and control technologies that would facilitate future access to space involve the automatic generation of ground/mission control software and test algorithms directly from engineering documentation (e.g., CAD/CAE files, network diagrams, operating criteria, measurement/information architecture, launch commit criteria, flight rules, hazard analyses), and the ability to generate software by directly interviewing subject matter experts utilizing "natural language" as a basis for control routines. While much of the above can be implemented via standards, technologies such as cloud computing can also be used to make these visionary advances a reality. While no particular technology research is required by NASA in this area, the evolution in computing capability should be closely monitored by NASA for use in developing command and control infrastructure for future missions.

2.2. Environmental and Green Technologies

Environmental requirements are always a major concern for ground and launch operations. Flight systems require toxic chemicals for fuel and prodigious quantities of water to quench flame and suppress noise. They create acoustic problems and emit environmentally challenging waste. The environmental scars from current ground and launch operations and those left behind by former programs (contamination in the soil and on obsolete infrastructure, improper waste disposal) have been costly and time consuming to remediate and mitigate. Technology advances are needed to address the challenges of material degradation (corrosion), contamination cleanup, waste disposal, renewable energy, and preservation of natural ecosystems.

2.2.1. Corrosion Prevention, Detection, and Mitigation

The total annual estimated direct cost of corrosion in the U.S. in 2010 is $578 billion—approximately 4.2% of the nation's Gross Domestic Product (GDP). In the U.S. defense sector alone, corrosion was estimated to be one of the largest components of life cycle costs for military weapon systems. Although corrosion management has improved over the past several decades, the U.S. must find better ways to encourage, support, and implement optimal corrosion control practices and pursue emerging technologies in this area.

For NASA, the severe degradation of structures from corrosion (caused by exposure to high temperature, humidity, salinity, sunlight, or highly acidic launch exhaust, use of dissimilar metals, standing/trapped water, etc.) has resulted in significant ground operations corrosion-related costs for inspection and maintenance of structures (launch pads, gantries, radars, buildings, etc.), medium- and large-scale blasting and repainting activities, and repair/replacement of structural metal elements that have seriously corroded. Using "coatings" is the most common way of protecting materials/structures from deleterious environmental effects. Coatings have a limited lifetime and have to be removed and replaced periodically, which generates waste, increases cost, and decreases the availability of the structure. In addition, the most effective coatings are known to have toxic effects on humans and the environment. Environmental regulation changes have dramatically reduced the production, handling, use, and availability of conventional corrosion protective coatings. As these regulations become more stringent, paint manufacturers have been phasing-out/discontinuing production and availability of coatings containing volatile organic compounds (VOCs)/hazardous air pollutants (HAPs), while restrictive emission standards for HAPs, human exposure limits, and waste disposal requirements have affected use and application to launch structures and ground support equipment. Finding a replacement for these coatings is an active area of research worldwide. NASA can achieve significant cost savings, for the space program and for the nation as a whole, by developing and implementing new corrosion prevention, detection, and mitigation technologies that provide environmentally friendly (no toxic materials) corrosion resistant/protective materials, coatings, and systems that last longer, require fewer reapplications, lower maintenance and inspection costs, reduce corrosion related damage/structural failures, cost less to dispose of, and create less environmental contamination. Technology work has been started to develop a smart, multifunctional, environmentally friendly paint system that detects and signals corrosion, mitigates corrosion, and self heals mechanical damage. The smart corrosion sensing and control functions are embedded in a high performance (ph-sensitive) coating that detects and responds actively, in a functional and predictable manner, to changes that occur when a material degrades as a result of its interaction with a corrosive environment. The autonomous corrosion indication function provides for early detection and location of corrosion, prior to the appearance of visible rust on the surface, which allows for minor surface coating touch-up versus repair/replacement of seriously degraded structural metal elements. The autonomous corrosion mitigation function provides environmentally friendly inhibiting compounds for increased corrosion resistance. The autonomous self healing function provides film forming self healing agents to repair mechanical abrasions or scratches to coating surface, reducing maintenance. Partnerships are in place within the defense industry (for vehicle and marine applications) and automobile and paint manufacturing industries to develop proactive corrosion control technologies, replacing the current reactive state-of-the-art practice of repair and refurbishment after a failure or problem occurs.

Other mission pull technologies include:

- Near-term development of coating alternatives to protect structures from corrosion. Examples include environmentally friendly coatings (no/low VOC waterborne or no VOC powder coatings), corrosion preventative compounds (coatings for ferrous/nonferrous metallic substrates without additional pretreatment and priming steps), organic corrosion inhibiting polymer additives for corrosion protection, and electroceramic coatings (nonchromated pretreatments based on titanium oxides from electrically assisted hydrolysis of metal complexes) to replace chromate conversion coatings.
- Midterm development of corrosion-resistant materials and coatings to minimize inspection, maintenance, repair, and refurbishment requirements, including high/low temperature corrosion-resistant materials (composites and ablatives), refractory materials for launch pad flame trench that provide acceptable performance and maintain integrity during/after exposure to launch environment without liberation of material and with minimal cracking, and low-melt polyimide composite conductive coatings to provide high performance, corrosion-resistant properties to metal surfaces.
- Far-term development of corrosion resistant structures, including corrosion-resistant alloys, (e.g., most commercial alloys, especially high-

strength aerospace alloys, contain several types of intermetallic phases [IMPs]; corrosion of aluminum alloys is essentially a microgalvanic process between these phases and the matrix alloy; identifying the IMP for aluminum alloys that provides mechanical strength with a minimum electrochemical galvanic coupling effect can allow for the development of new aluminum alloys with these IMPs), corrosion-resistant polymer composite structures/equipment, corrosion-resistant extended life materials, and maintenance-free coatings (smart material formulations with corrosion functions that adapt their properties dynamically to changes in the environment).

Mission push technologies include development of autonomous, self-healing structures (e.g., composite structures with diagnostic/prognostic fault detection and self-repair capabilities for high-performance polymer surfaces), corrosion-hardened materials that perform without degradation or the need for coatings or repairs (e.g., material formulations with functionalities that enable autonomous monitoring and mitigation, in real time, of a variety of environmental factors), and corrosion-free structures (self-diagnosing and self-repair materials).

A 20-year life cycle cost analysis performed in October 2009 detailed cost savings with technology investment in developing a smart, multi-functional, environmentally friendly paint system ($160M) and high-performance refractory materials for the launch pad flame trench ($32M). There is high confidence that the development of corrosion-protective launch pad coatings and corrosion-resistant flame trench refractory materials will be achievable within the stated timeframes because both technology tasks were formulated under ETDP.

2.2.2. Environmental Remediation and Site Restoration

For years, the chemicals and materials used on ground facilities and equipment and during launch processing operations have contributed to major environmental contamination of soil, groundwater, and other areas that often require extensive and hazardous removal and disposal. Cleanup efforts are extremely costly due to the extent of contamination and timing of the remediation efforts (noninterference with operations and end-of-life cycle use), limited large acreage capabilities of COTS systems, labor intensive and inefficient removal processes, and generation of hazardous by-products.

Technology advances need to focus in the near- to midterm on rapid, highly effective pollution and contaminant removal from multiple media (water sources, groundwater, soil, sediment, structures, etc.). There is a national (if not worldwide) need for technology that effectively removes Dense, Non-Aqueous Phase Liquid (DNAPL) contamination from groundwater sources. Emulsified Zero-Valent Iron (EZVI) is a significant new technology developed by NASA best suited to remediate groundwater contaminated with chlorinated solvents. EZVI was selected in 2005 as a winner of both the NASA Government Invention of the Year and NASA Commercialization Invention of the Year, as well as the 2006 Award for Excellence in Technology Transfer by the Federal Laboratory Consortium. EZVI has been licensed to six companies.

Approximately 63% of all sites on the Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) National Priority List for contaminated soil treatment[5] have heavy-metal contamination, with lead, chromium, cadmium, and copper. Once heavy metals reach the environment from sources such as domestic and industrial effluent, they are persistent and cannot be biodegraded. The sediments can act both as sinks for pollutants and as sources of aquatic contaminants. Natural and human disturbances of the sediments can release the contaminants to the overlying water, where bottom-dwelling organisms may be exposed through direct contact, ingestion of sediment particles, or uptake of dissolved contaminants in the water. Similar methods for cost-effective remediation need to be developed (e.g., liquid-membrane and nano-particle emulsions, catalyzed nano-scale metals) to address removal of heavy metal and other contaminates from soils, sediments (in harbors, drainage ponds, and riverbeds), painted surfaces, caulking materials, and building equipment and, in the midterm to far-term, to cover large areas of contamination and respond with real-time remediation when the contamination occurs (through diagnostic sensing and rapid response systems).

Technologies for environmentally friendly remediation of hazardous waste (fuels, materials, liquids, air pollutants, etc.) also need to be developed

5 *http://nlquery.epa.gov/epasearch/epasearch?fld=ordntrnt&areaname=Superfund+Innovative+Technology+Evaluation&areacontacts=http%3A%2F%2Fwww.epa.gov%2Fnrmrl%2Flrpcd%2Fsite%2Fcontacts.html&areasearchurl=&result_template=epafiles_default.xsl&filter=samplefilt.hts&typeofsearch=area&querytext=contaminated+soil+treatment*

in the near-term to midterm to address detection (e.g., hyperspectral and thermal remote sensing, low-level hypergol vapor), treatment (e.g., low waste hazardous commodity filtration for mixed fuel wastes and environmentally friendly scrubbers) and safe disposal (microwave technology for the destruction of hypergolic propellants); and in the far-term to address capture (nonhazardous and environmentally friendly vapor capture) and neutralization systems (chemical/electrical deactivator and degradation agents).

Mission pull technologies include development of systems to degrade hazardous fuels/materials and convert them into usable inert materials for reducing hazardous waste streams and enabling regenerative systems, including polymer electrolyte membrane systems for the treatment of high concentration hypergolic waste and conversion of the propellant waste fuel into ambient gases, and autonomous detection/neutralization/remediation systems.

2.2.3. Preservation of Natural Ecosystems

Regulatory activities have identified carbon and nitrogen as chemicals of concern for the nation. NASA ground and launch operations produce carbon, and carbon dioxide, which are linked to greenhouse causes of climate change and nitrogen, which is identified as a pollutant causing eutrophication of freshwater ecosystems, i.e., rapid increases in amounts of plant nutrients that speed up plant growth and eventually choke out animal life. Carbon sequestration and nitrogen removal technologies, such as creation of bio-char and optimized controlled burning of wild lands, will enable federally mandated emission reduction goals to be met. Pyrolysis of organic waste streams (e.g., biomass from exotic plant removal programs) generates a charcoal, or biochar, which can both improve soil fertility and sequester carbon when incorporated into soil. This provides alternative approaches for managing disturbed lands (e.g., abandoned citrus groves) and supports launch site land management practices to reduce facility carbon footprint. Other technologies to maximize carbon sequestration include waste pyrolysis, carbon flux systems for measuring carbon uptake and/or efflux in the wetland ecosystems, and new concrete aggregates/binders that sequester carbon dioxide without losing strength.

In most coastal areas, there is a need to better understand the relationship between surface and shallow surficial groundwater systems to evaluate stormwater flow and management, storm surges, impacts of the predicted rise in sea level, and influences on vegetation and protected wildlife habitats. Surface and surficial groundwater are linked by the infiltration and vegetation evapotranspiration processes. Technologies include development of multispectral thermal or hyperspectral imaging systems to map evapotranspiration rates for the various coastal communities. Ground and launch operations produce nutrient runoff and pollution of surrounding estuaries (e.g. launch exhaust/chemical deposition and washdown water collection, treatment and release into the surrounding environment) which are environmental concerns.. Technologies for on-site treatment and water recycling systems (e.g., hollow fiber membrane bioreactors for wastewater processing) coupled with septic water treatment systems to break down organic compounds and nitrogenous waste will prevent contaminants from draining into groundwater or coastal estuaries.

Technology development to enable environmentally friendly ground processing will also minimize the impact of operations on the ecosystem. Mission pull technologies include development of rehabilitation systems for surfaces and structures using nontoxic materials and chemicals (100% bio-based corn-blasting media as an alternative to plastic, citric acid as a nonhazardous alternative to nitric acid for passivation of stainless steel), acoustic dampening and abatement systems (energy absorption materials, acoustic source noise cancellation systems), toxin-free surface preparation systems to reduce hazardous streams (e.g., laser-based substrate preparation for coatings, adhesives and corrosion inhibitors to elimination chemicals used to etch and activate substrate surfaces, laser-based coating removal to eliminate sandpaper, blasting media, and chemical etchants/strippers), and nontoxic waste streams (e.g., liquid nitrogen technology for use in stripping coatings from various substrates to eliminate contaminated blast media and water currently used for coating removal).

2.2.4. Alternate Energy Prototypes

Technology advances are essential for maximizing the use of renewable resources and efficiency in energy production and distribution. There are also opportunities for new green fuel technologies for more efficient alternative fuels for vehicles, generators, equipment, and launch vehicles. Examples of such technologies include:

- Near-term development of megawatt solar photovoltaic power generation systems (consuming no fuel/water, generating no waste) that produce enough electricity for dramatic reductions in carbon dioxide, sulfur dioxide, and nitrogen oxide; and cost-effective green diesel alternatives to fossil fuels (microcrop technology that produces green diesel and a high-value protein food source in an environmentally beneficial manner) that absorbs carbon dioxide from greenhouse gas emissions.

- Midterm to far-term development of solar concentrators for delivery of light through fiber-optic cables to protected environments to eliminate the power requirements for electric lamps and delivery of solar power for treating and decontaminating wastewater or for photocatalytic control of air contaminants that build up in tightly insulated buildings; wave-powered generators using electro-active polymer technology deployable on ocean buoys; and the creation of an "energy garden" where emerging, renewable energy technologies (solar, wind, wave energy, hydrogen fuels, biofuels, etc.) could be demonstrated and tested while adding power to the energy grid.

Far-reaching technologies involve development of alternate energy sources (i.e., harvesting energy from lighting, radio frequency waste, launch by-products, electromagnetic radiation) that will benefit not only NASA but also the nation in spin-off applications that can help conserve valuable resources and preserve natural resources for future generations. Waste-disposal-driven power technologies include advanced waste-incinerator-driven power generation that is an alternate source of electrical power as well as an efficient means for disposal of all forms of waste, replacing present landfill and sewerage process functions, and a co-generation-driven freshwater desalination system that uses waste energy from the waste-incinerator-driven power generation system.

Green materials and structures will reduce energy costs for buildings, reduce storm runoff and groundwater pollution, and increase the life span of structures. For example, the incorporation of living plants into roof and wall structures is a rapidly emerging environmental technology that offers many benefits related to the internationally recognized Leadership in Energy and Environmental Design (LEED) green building certification system. The effectiveness of specific designs (with varying plant species and growing approaches) is dependent on local climate. Depending on the approach, food production could supplement local agriculture.

2.3. Technologies to Increase Reliability and Mission Availability

The current approach taken by NASA and the defense industry to ensure the reliability and availability of ground and launch systems is a combination of design strategies and operations concepts that depend heavily on the use of redundant systems and elimination of single points of failure. Frequent preventive maintenance, calibration, or replacement of critical hardware is routine. A highly skilled, highly trained cadre of engineers, operations personnel and support staff, as well as launch infrastructure, must be developed and maintained to integrate, test, and validate ground and launch systems and help ensure system reliability and availability. This approach is costly but, in spite of all the steps taken to ensure supportability, availability goals have been difficult to achieve. Based on a 2008 study performed for the Shuttle and Launch Services Programs, the launch availability rate of the Space Shuttle Transportation System was roughly 54%, and the Delta II was approximately 56%. The airline industry had 98.5% flight availability (i.e., flights not being cancelled) for the period August 2009-August 2010.

Clearly, in order to achieve the nation's goals for timely, affordable access to space, and meet optimistic launch availability rates of new space transportation programs, which exceed 95%, technologies must be developed to produce greater reliability and availability; minimize infrastructure, maintenance requirements, and vehicle processing times; and reduce the size of ground and launch crews.

Integrated systems or vehicle health management technologies, commonly referred to as ISHM/IVHM, will capture design and operations knowledge about the function and interaction of ground and vehicle systems and automate and integrate functions associated with anomaly detection, fault isolation and recovery with existing capabilities. Sensor and wireless technologies will be integrated with ISHM algorithms that perform anomaly and fault detection, fault isolation and prognostics to produce intelligent devices that can self-detect and identify faults, failures or anomalous reporting. Working in concert, intelligent devices will be able to exonerate or confirm the health of other sensors and devices. ISHM and intelligent devices will be integrated in pathfinder demonstrations to mitigate the risk of developing automated and autonomously operating systems for ground and range operations. Robust, flexible, fault-tolerant architectures will be developed to seamlessly integrate ISHM technologies, enhanced ground and launch support devices and equipment, and robotic systems with ground and launch systems and processes; the net effect will increase system reliability and launch availability and reduce the cognitive workload and dependence on human operators while still retaining a role for the human in decision-making, where and when necessary.

2.3.1. Advanced Launch Technologies

Various launch concepts and configurations were included as a means of ensuring (1) common challenges to ground and launch operations were addressed and (2) crosscutting capabilities and technologies that would benefit multiple vehicle architectures or launch configurations were developed. It is expected that configuration- and architecture-specific launch assist technologies would be added to the investment portfolio through periodic review of the Agency's roadmaps and as launch architectures and concepts evolve and mature.

Establishing new ground and launch facilities or launch sites is difficult in today's launch environment. New facilities and launch sites, under environmental and safely guidelines, must be sited away from populated areas to protect the population, workforce, and sometimes wildlife, from noise, the potential of explosion, and other hazards. Unpopulated areas, however, typically require new facilities and other infrastructure to supply commodities, such a power and water. Reusing existing facilities can be problematic because many facilities are designed for a specific vehicle configuration or require costly modifications to use for a different vehicle, or are not sized adequately to support more than one vehicle at a time.

Interoperability, multiuse systems and structures, such as a common integrated umbilical plate and autonomous flight safety systems will minimize launch infrastructure. Systems health management technologies will help achieve more robust systems designs and will improve system availability, which will reduce the dependence on redundancy as a means of ensuring system availability and will also help to reduce infrastructure requirements. Automation, interoperability and systems health management technologies will also reduce workforce requirements for a single launch operation, and enable ground and launch personnel to support multiple and diverse missions from the same or different launch site.

Technologies that absorb energy or minimize acoustics (e.g., energy absorption air bag curtain materials, acoustic source noise cancellation systems, blast-hardened structures) will allow a reduction in the quantity distance requirements for locating launch structures and facilities. Inflatable or deployable launch vehicle shelters (e.g., atrium environment processing areas containing all or clusters of facilities for reduced footprint, reduced operations interruptions, and safer processing areas) and reconfigurable facilities (e.g., morphing flame trenches, air-bearing foundations and equipment on a smooth pad) minimize launch pad/support systems footprint. Portable test equipment and control center capabilities (e.g., self-contained portable on-demand (POD) payload systems with no vehicle interfaces), communication architectures that allow local or remote launch operations, high-fidelity process models and a virtual launch and range environment will enable planning, test, and checkout from multiple and remote locations and rapid-response ground and launch operations at existing or new launch sites.

Horizontal space launch assist is an alternative advanced launch technology that could dramatically reduce launch costs; lower maintenance with high multi-mission reliability; improve turnaround launch cycle; enable safer, low-elevation ground operations; provide safer abort capability; and transfer green technologies to other sectors. Although this roadmap only addresses the horizontal launch assist technologies and not the launch vehicle or launch propulsion components, only a comprehensive ground and flight systems technology development strategy would provide benefits. Candidate electric ground launcher technologies include linear synchronous motors, linear induction motors, and rail gun motors. Nonelectrical candidates include combustion gas piston-based launchers and rocket sled systems. All are characterized by very high power delivery but low energy requirements.

Each of these candidate technologies exists in other applications but current capabilities do not meet the requirements for horizontal launch assist. Linear electric motors are used on high-speed trains but do not exceed Mach 0.5 in operational use. Rail gun technology is capable of accelerating small conductors to extremely high velocities but has not been used in large mass, low acceleration scenarios. Magnetic levitation eliminates friction but has stability issues as speed and vibration increase. Gas piston launcher technology was tested by Reaction Motors in the 1960s for naval catapult use but very long piston launch systems have never been built for variable G forces and much higher launch velocities. Each of these technologies requires advances in the launcher itself and in ancillary systems; for example, electric launchers will require electrical power storage systems capable of very high and variable power delivery rates. A gas piston system will require a robust and efficient gas generator system and probably to be distributed down the length of the drive cylinders. Consideration must also be given to hybrid launchers that combine technologies for optimal performance. High-speed systems (above Mach 0.5) are at approximately TRL 2 to 3. Development of ground based launch assist technologies will be coordinated with TA 1 (Launch Propulsion Systems).

Ground launch assist systems can be used to provide some fraction of the ascent velocity requirements of suborbital and orbital vehicles, thereby improving range or payload mass capabilities for a given vehicle size, or alternately, allowing reductions in vehicle size. Initially, small-scale feasibility studies and pathfinders for alternate launch assist concepts will include:

- Launch tube pad concept: enclosed launch pad to eliminate roll out, separate launch tower and assembly building. Technologies involve development of a material expansible liner that comes out of the ground before launch to form a launch tube. Major cost savings could be realized by eliminating multiple facilities and GSE.
- Underwater "flotation" launch assist: technologies involve development of a launch tube (sealed with a diaphragm or cap at the exit) that can be submerged and anchored to the ocean floor. At T-0, inflatable floats are activated, anchors are released, and the entire launch tube is accelerated from depth to the surface by the flotation devices (via Archimedes principle). As the tube penetrates the surface of the water it is already traveling at a vertical velocity enabling a rocket to ignite and launch out of the tube, gaining an assist from the floats.
- Driven harmonic oscillator trampoline launch assist: technologies involve development of a trampoline system that can propel a rocket vertically upward, over and over, utilizing elastic energy absorbers. A harmonic impulse is delivered at the bottom of the oscillation, thereby propelling the rocket higher, this is repeated a number of times with the rocket going higher each time. Finally the rocket propulsion system is ignited at the peak altitude.
- Horizontal water launch assist: technologies involve development of a rocket powered hydrofoil sled with a ground effects aerofoil system which provides a large horizontal velocity vector to an attached launch vehicle as it accelerates over a large distance across the water.
- Zeppelin dirigible launch assist: technologies involve development of a high altitude launch platform capable of being suspended by four zeppelin dirigibles at each corner and flown to a high altitude, enabling a horizontal rocket to be rolled off the platform and then subsequently ignited.

2.3.2. Environment-Hardened Materials and Structures

The materials, components, and systems used in launch environments endure extreme conditions in regard to humidity, pressure, temperature, wind, vibration, and radiation. Such harsh conditions result in failures and necessitate frequent maintenance or other measures to maintain systems in a healthy state. In addition, current techniques for shielding or ruggedizing equipment to operate in these environments increase the weight of flight hardware and reduce its accessibility. However, failures often still occur, resulting in schedule slips and possibly launch delays.

Material degradation that results from the interaction with the environment is a serious problem that affects the material's performance. New materials that will not degrade in the aggressive environments in which NASA accomplishes its mission will radically reduce the cost and increase the safety, efficiency, and sustainability of NASA's mission with minimal deleterious effects on the environment.

Degradation-resistant lightweight materials and structures can be developed with the functionalities that enable autonomous monitoring and mitigation of a variety of environmental factors that affect ground support structures, equipment, and vehicle performance, such as those produced by exhaust from rockets and engines, changes in the electric field, and electrostatic charge buildup on equipment or spacecraft surfaces. These materials will compensate in real time for these changes, allowing extended use of materials in launch complexes and vehicles to be launched under a wide range of weather and environmental conditions.

Technologies to resist degradation will involve development of temperature hardened materials, electronics, and structures (e.g., low-flammability materials), puncture and abrasion resistant materials, thermal protection/ insulating materials (e.g., ablative or composite, "ice-o-phobic," refractory composite materials), blast/explosion resistant materials and structures (e.g. energy absorption materials, blast reflective or counter blast designed support structures), lightning/radar hardening of vehicle and components (e.g., lightweight materials, conductive composites, shielding using fiber optics), electrostatic charge build-up resistant materials/coatings (e.g., nonaccumulating, discharge, and noncontaminating neutralization materials, coatings that increase the decay rate of charged materials, switchable materials that will become electrically conductive in the presence of rising electric fields and electrostatically dissipative when charge starts to develop), and weather hardened structures (electromagnetic interference, radio frequency, and laser shielded systems).

2.3.3. Inspection, Anomaly Detection, and Identification

Inspections are most often accomplished either visually or via specialized instrumentation and require extensive use of time and labor, thereby making operations less efficient and ground service more expensive. Procedures often require ground crews to "break" a system configuration to determine if the system is broken. Often the inspections are intrusive, requiring access to hard-to-reach locations and the installation of platforms. In addition, the technicians may have to interrupt or dismantle other systems to access the suspect system, which in turn may require additional inspections, testing, and system verifications as the systems are put back together. The more access required and the more systems that need to be dismantled/interrupted, the greater the cost and chance of collateral damage and the longer the processing and validation time. Technologies will need to be developed for noninvasive, nondestructive lab and field inspections to minimize the impacts to the vehicle processing time line and program life-cycle costs.

Anomalous conditions frequently occur during offline testing or during real-time launch operations. Because the interactions between ground and launch systems are complex, there are often many contributing factors. Because these factors may occur in multiple dimensions, pinpointing, or even recognizing the existence of, an anomaly is often difficult or impossible until after a fault or failure has occurred. Highly skilled experts can sometimes recognize the emergence of anomalous conditions for well-understood operations but achieving that level of expertise can take years. Anomaly detection technologies will be developed to autonomously monitor ground testing and launch operations and notify operators or a higher-level autonomous agent, such as the command and control software system, of anomalous conditions. Early intervention, preventing system damage, and reducing remediation cost are some of the benefits expected from these technologies.

Nondestructive evaluation (NDE) and inspection techniques are required to verify material and structural integrity before launch or after a potentially damaging event. NDE technologies are well-established (e.g., ultrasonics, X-ray, dye penetrant) but the growth in new aerospace materials and processes continues to present challenges. In addition, the use of large composite structures and TPS materials can significantly increase inspection requirements and drives the need for expensive and difficult procedure certifications (e.g., probability of detection studies). Handling, processing, and damage tolerance detection methods for large composite solid rocket cases will be coordinated with TA-1 (Space Propulsion). Some structures, such as windows, will require highly specialized equipment to be developed and tested.

Non- and minimally intrusive sensors, actuators, instrumentation and devices with embedded intelligence and plug-and-play capabilities will be developed to support localized and broad area monitoring in both wired and wireless configurations for ground and range operations. The functions performed include

- detection of gas, fluids, vapors, fire, defects, contaminants, and impacts, or collisions;
- determination of strain, weight, gauge;
- determination of cryogenic liquid levels and flow rates;
- multispectral imaging;
- detection and identification of objects; and
- portable cleaning, sampling and testing.

Capabilities will be developed to sense chemical, gas, pressure, temperature, flow rate, humidity, velocity, acceleration, force, vibration, position, proximity, sound, electrostatics, and electromagnetics. Multi-parameter sensors, multi-sensor arrays and algorithms to fuse information from multiple or non-heterogeneous sensors, instrumentation and devices will also be developed. It is assumed that as technologies mature and program and mission objectives are formulated other sensing capabilities may be required. As the need for new capabilities evolve, it will be important to ensure technology development efforts focus not only on the sensing element but also on minimizing calibration cycles and embedding systems health management technologies into the sensor platform, and enabling plug-and-play capabilities. Supporting technologies will be accomplished through TA-8 (Science Instruments, Observatories, and Sensor Systems).

Radio frequency identification, scanners and other sensing technologies will be used to develop self-annunciating systems and port-of-entry systems in order to decrease the time and resources required for logistics management. Systems heath management technologies will be combined with tracking technologies to provide health and status information about parts, components and assemblies from the factory through shipping, storage, installation and operational use. Tracking technologies will also be used to detect counterfeit parts/authenticate parts, verify configuration, and locate parts or personnel. NASA will coordinate with the Department of Defense (DoD) to leverage current research in frequency management, identification tag sensing and recognition. NASA will also coordinate with industry to leverage technological advances in shipping, handling, tracking technologies and logistics and supply chain management techniques.

2.3.4. Fault Isolation and Diagnostics

Fault isolation in today's ground and launch environment is performed by highly skilled engineers and operations personnel using a combination of techniques and information, including design artifacts, data analysis, experience, past problem reports, and engineering notes and troubleshooting. Current and future goals are to minimize the dependence on humans to isolate failures and diagnose problems, but complex interaction of ground and launch systems can make it difficult to quickly isolate the cause of anomalies and failure.

In order to reduce the cognitive workload on human operators and minimize the number of personnel required to support a single launch operation, fault isolation and diagnostics technologies will be developed to enable self-diagnosing components, systems, and materials and common-mode failure identification, in-flight maintenance and fleet supportability. This will reduce troubleshooting times and result in improved availability. Fault models, highly fidelity simulations and physics-based models of ground and range systems will be developed to accurately represent complex system functions and fault propagation paths. Complex interactions between integrated systems which could precipitate faults or failures in other systems will also be modeled and the models, in combination with command and control and simulation capabilities will speed the identification and isolation of suspected or failed components. Technologies will also be developed and integrated with sensing technologies to detect collisions or impacts and make inferences about impact damage and its effect on system operation. Automated fault analysis can also be used to develop conditions and timing that might lead to crew abort or flight termination.

Other technologies will be developed, such as wireless connective and intelligent devices with embedded intelligence, which will autonomously assess and report their health and overcome faults or failures by self-reconfiguration. The use of intelligent devices will increase component reliability and reduce requirements for spares, testing equipment, and maintenance requirements.

2.3.5. Prognostics Technologies

Because reliable predictions about component or system failures cannot be made in today's ground and launch environment, redundant components and systems are commonplace and critical components are often replaced after a few uses, or even a single use, to avoid the risk of system failure during a ground or launch operation. Prognostics technologies will be developed to estimate the remaining life in a component, material, or system and predict the time when it will no longer perform its expected function. By predicting the time remaining before a system will move outside its operational boundaries, prognostics technologies will enable mission planners and operations personnel to develop more accurate supportability plans, reduce redundancy requirements, and make informed decisions about the ability of a system to complete an operation. Prognostics capabilities will be developed for electronics and other ground and range devices and equipment, materials, structures, wiring, cables, and harnesses. Prognostics capabilities will be integrated with other ISHM capabilities to provide portable and in situ health management capabilities for ground and range systems.

An example of integrated prognostics with fault detection, isolation, and recovery (FDIR) is the development of smart wiring system technologies to address aging wiring issues in flight and ground systems. State-of-the-art wiring constructions and manufacturing have remained essentially unchanged for decades. Several of the major limitations of current wiring insulation are that it tends to crack and fray as it ages, and is susceptible to maintenance-related damage during ground processing. These problems can be very difficult to detect in complex systems. The most common method of finding wire faults is still visual inspection, which is highly unreliable (detecting only grossly damaged wiring), costs many personnel hours, requires system shutdowns, and raises the potential for inadvertent collateral damage to surrounding systems. Smart wiring systems will have the capability to detect, locate, repair or mitigate an electrical compromise on either an energized "live" wire during functional operations or a "dead" wire during maintenance operations. The in-situ monitoring system will use defect detection techniques (e.g., Time Domain Reflectometry) to identify and locate problems such as opens, shorts, chafing, and degradation, and intermittent faults that lead to wiring system failures. Physics-based models will be used to advance technologies for innovative detection systems, monitoring of insulation degradation and arcing effects, and prognostics capabilities to predict when a wire is going to fail and determine the remaining useful life of the wiring system. Wire insulation materials will be developed in a unified (where self-healing and detection technologies are closely integrated into the wire insulation) and a layered approach (where different layers of the wiring system have different functions) to maximize functionality without impairing electrical performance. Once damage has occurred to a wire, the fault will be isolated by a re-routing device and power transferred to a spare wire to maintain system functions. The insulation material will either self-heal completely or, in cases where the damage to the insulation is too large for self-repair, require manual repair as diagnosed by the monitoring system. Once the damage has been healed or repaired, the spare wire used in the power transfer is freed up for use as a spare wire for the system. The health of the wiring system is continuously monitored after the mitigating action. Reconfigurable connectors/switches will allow for real-time mitigation of failures. The integration of detection technologies with fault mitigation technologies will provide a robust wiring system that has the capability to be both diagnostic and prognostic, greatly improving safety and reducing life cycle cost.

A 20-year life cycle cost analysis performed in October 2009 detailed cost savings with investment in smart wiring system technologies ($154M) and FDIR technologies to prevent a launch scrub and reduce calibration and maintenance of transducers ($105M). There is high confidence that the development of these technologies will be achievable within the stated timeframes because both technology tasks were formulated under ETDP. This technology solution is also critical for space exploration missions to reduce program risk (loss of crew due to system failures) and life cycle costs (for logistics re-supply). Wiring is a key component of spacecraft and accounts for substantial weight and space consumption. It is highly desirable that future wiring systems be made of smart materials; consist of highly integrated material systems that incorporate embedded electronics, sensors, and actuators; and be multifunctional and adaptive so they can be reconfigured in response to changing mission conditions. These systems must also be reliable, affordable, safe, light weight, small in volume, and sustainable over long periods. In-flight, autonomous, continuous integrity monitoring, and in-situ self-repair and reconfigurability of systems to mitigate failures will greatly minimize crew impacts for in-flight maintenance or repair and increase reliability of systems and subsystems.

2.3.6. Repair, Mitigation, and Recovery Technologies

Many of the operations associated with maintaining, testing and repairing, ground and launch systems or recovering from failures are time and labor-intensive. In order to achieve today's launch availability rates, a large number of ground and launch personnel are needed to support a single launch operation. To decrease the time to maintain, test, and repair systems and to reduce workforce requirements for a single launch operation, technologies need to be developed to enable self-repairing, self-configuring materials, components, and systems. Technologies will be developed and integrated with other ISHM technologies to automatically identify and initiate the correct procedures to repair or recover ground and range systems to the desired function or to mitigate the impact of existing or impending failures. These technologies will enable systems to avoid failure or continue operations with degraded performance if continuation is deemed safe and practical. When it is not possible or practical to continue, these technologies will terminate system operation until human or robotic assistance can restore system function. As parts fail or near the end of their useful life (a function enabled by prognostics technologies), automated and autonomous systems will inform the command and control or logistics management systems and enable condition-based maintenance and just-in-time supply chain management.

2.3.7. Communications, Networking, Timing, and Telemetry

A wide variety of communications technologies would improve how NASA communicates within the new exploration paradigm. Data will always be required in support of crew safety, science, research and public outreach, but many revolutionary steps should be taken to improve communication with robotic and human exploration missions. Setting an operational goal to develop a suite of technologies to support on-demand/adaptive communications would significantly reduce the existing arduous task of planning and scheduling flight/ground telecommunications activities, thus reducing life cycle costs. These new technologies would automatically choose the best available communications configuration for optimal data return.

Intelligent aperture systems, dynamically configurable telecom-command and data handling (C&DH) avionics throughput, enhanced data compression algorithms, software-defined radios, advanced networking protocols, intelligent network topologies, highly secure and access-controlled flexible data networking, on-demand dynamic frequency allocation, and beacon communications are all technologies that should be infused into U.S. and international assets to create an integrated low-cost, operable telecommunications network.

Advanced telemetry systems are an essential part of the new range operations solution. Robust systems are required to ensure mission success. Present telemetry systems are complex systems requiring extensive ground infrastructure, with time-consuming and labor-consuming reconfiguration efforts. New technologies are needed to support these goals while providing cost-effective solutions. Free space optics and millimeter wave communication technologies will be developed to support this effort. Unified precision timing sources are also needed to support ground operations. Architectures and standards to support the use of sensor networks, data fusion, wireless power and data transfer, integrated health management technologies and optics for local, remote, portable and autonomous launch and range operations will be developed.

2.4. Technologies to Improve Mission Safety/Mission Risk

Increasing safety and reliability of operations in the launch and landing periods is imperative to provide efficient access to space. Technologies such as robotics and human-system interfaces can be developed to make ground operations safer. Weather-related technologies will maximize efficiency, allowing for more launches in any given time period. As these technologies are being developed, our nation will need more frequent access to space and have more vehicles to track and communicate with than ever before. More frequent launches will mandate that our country make certain all commercial vehicles are safe throughout the ascent to orbit. Range technologies must advance significantly to track multiple vehicles and provide the necessary data needed for potential launch terminations. As having more launches directly relates to more reentries and landings, landing and recovery systems must be advanced to eliminate hazardous and costly land or water recovery operations.

2.4.1. Range Tracking, Surveillance, and Flight Safety Technologies

Throughout the launch systems processing phase and launch operations, the range is one of the most important and recognizable interfaces with the flight vehicle. During the launch of any space-based vehicle, accurate range tracking is essential for range safety, mission success, and post launch analysis. Insuring the range is clear of persons, ships and aircraft will be enhanced and made less expensive and more responsive by introduction of space based surveillance assets and "smart" sonobouys capable of detecting various water craft and capable of signal processing to determine vessel type, position, speed and bearing and transmitting the information to the range safety officer via a satellite relay. Space vehicles and abort systems will vary significantly in size and speed, driving development of new approaches to tracking. Also, in order to provide flexibility and on-demand support to customers, it is important to explore space-based range solutions (assets and architectures), to increase overall responsiveness and to provide a greater ability to track the entire course of a launch vehicle without expensive ground assets. These technologies will be used for visual and electronic tracking and will assist in quantifying mission safety/risk/success. Ultimately, onboard tracking, together with advanced telemetry systems and steerable beam antennas, responsive to vehicle position and attitude and conformal to the vehicle skin, will provide multiple simultaneous tracking solutions from the same launch site.

To greatly enhance the mission safety/risk field, new flight termination technologies must also be developed. Combining accurate and robust tracking technologies with autonomous onboard flight analysis, autonomous flight abort/termination, and new termination technologies will increase the ability to save an off-nominal mission and potentially save lives, while providing the ability to launch at any time, from any place in the world, and to support simultaneous missions. Incorporating innovative lasers and similar technologies that allow flight termination systems to be both ground and flight vehicle assets will provide a means to decrease costs and support multiple launches per day. Other technologies identified to help provide autonomous range operations include antijamming and anti¬spoofing communications capabilities, collision avoidance, ground- and space-based surveillance systems, remotely operated and autonomous unmanned aerial vehicles, and reconfigurable assets.

2.4.2. Landing and Recovery Systems and Components

Current landing and recovery operations for space flight vehicles pose many challenges that must be overcome if access to space is to become a routine and reliable transportation mode. With today's space missions, spacecraft that return to Earth do so in specialized, restricted landing zones in remote locations, with vehicle-unique handling equipment and highly trained personnel, which may have to travel to various landing sites in the eventuality that a contingency site is required. Postlanding operations can involve hazards such as the off-gassing of toxic propellants and fluids and high temperatures on vehicle surfaces caused by reentry into Earth's atmosphere. Prior to allowing the crew/passengers to exit or downmass experiments to be removed from the spacecraft, a hazardous and time-consuming operation to evaluate the environment around the vehicle must be performed. Ground support crews must wear protective suits before approaching the vehicle, perform a detailed visual inspection around the vehicle, scan the area for toxic gases and hot areas, and finally clear the area so that postflight operations can commence. The spacecraft is then connected to support services to maintain the safety of the crew, integrity of the vehicle, and to prevent contamination of space experiments. After postflight operations, transporting the vehicle to its re-servicing point is a slow, methodical process with support equipment attached to the vehicle to maintain the proper system conditioning.

Technologies need to be developed to compress the time required for landing and recovery operations and also to allow future landing and recovery activities to occur in a wider variety of potential landing sites and without specialized support teams. Automated Guided Vehicles (AGVs), complete with standardized servicing, an array of advanced sensors, precision alignment/berthing systems, and expert software agents, could be developed and brought into service. To account for fluctuations in flight trajectory, and using advanced surveillance, tracking, and auto-clamping systems, the AGV could "seek and grab" a returning spacecraft or spent booster segments before touchdown and return it immediately to a processing location anywhere. Near- to midterm technology advancements include advanced imagery and sensing systems to remotely scan the vehicle after landing to detect any hazardous off-gassing and high-temperature conditions, automated safing and reconfiguration systems for the flight vehicle, and wireless communication with high-bandwidth and high rates of data transmission to allow for autonomous download of mission and vehicle health data. Contamination protection systems need to be developed for processing downmass experiments that are removed from the vehicle post-landing (especially for extraterrestrial samples) to protect both the integrity of the sample and health of the handler/environment. Pathfinder technologies developed by the Centers for Disease Control (CDC) for containment of hazardous pathogens (sensing, filtration, handling, transfer, and containment technologies such as portable clean rooms) can be used for these types of NASA applications. Other far reaching technology advances for supporting a wide range of architectures include autonomous precision landing systems, autonomous safing and reconfiguration systems, advanced air bag landing systems, short runway vehicle arresting systems, energy absorption foam filled landing pits, and possible ground based power beam assisted vertical landings.

Automated landing and servicing operations on the ground could be a precursor for similar operations on planetary/lunar/asteroid surfaces. Surface operations will require autonomous, deep-expert capabilities. With the AGV concept, a spacecraft could land on a planetary surface in a manner that eliminates dust and debris near a habitation/ISRU location. Conversely, the AGV could gently "lift" the spacecraft to a safe elevation, detach, and safely clear for a delayed ignition, minimizing debris on the surface.

2.4.3. Weather Prediction and Mitigation

Adverse weather conditions continue to be major impediments to the ability to launch and land a space vehicle at any time desired. While the most important factor in increasing this ability is a robust vehicle design, there are important considerations to be made in the future design of ground capabilities. First and foremost is improved weather forecasting. The most promising capabilities lie in the development of comprehensive and real-time databases integrated with sophisticated data fusion and decision support display capabilities.

Progress towards this goal is being made today through collaboration between NASA and other federal agencies. This project is developing the NextGen database to continually share national airspace data in real time to support air traffic management and safety. The NextGen system will include meteorological, space environment, and oceanographic data assimilation and prediction. The Weather Information Database (WIDB), aka, the 4-D Weather Data Cube, will provide a common, consistent, and reliable source of information to multiple users for decision support. Part of the WIDB will be the Single Authorative Source (SAS), which will provide a common weather picture to be the basis for aviation decisions. The SAS is a merger of model data, automated algorithms, observed data, and input from meteorologists. This common data system will support launches and landings as well as recovery operations by aircraft and ship. Mission push technologies would include enhanced sensors mounted on unmanned air vehicles (UAVs) and ultimately, autonomously controlled space-based assets. Space-based meteorological sensors that expand the current capabilities to obtain measurements of wind, turbulence, temperature, density, and sea state would provide not only improved weather forecasting at one launch site, but could provide a consistent and reliable forecasting ability for use by all launch sites across the globe. In the long-term, these space-based assets could provide the basis for Martian and other nonterrestrial weather forecasting systems.

In addition to forecasting weather conditions, significant improvements to launch and landing capabilities will be achieved if a practical method for operating vehicles in the presence of lightning were developed. This calls for the development of a 3-D real-time system to measure electric fields. The lightning launch commit criteria in use today are thought to be overly restrictive. However, the fundamental physics of natural and triggered lightning is not known well enough to permit a risk-based analysis and revision of the criteria. Recent limited revisions to some of these criteria resulted only after expensive one-time field experiments were conducted. The development of a real-time in-situ or remote capability to measure the atmosphere's 3-D electric field would provide a significant improvement to the understanding of this important parameter, as well as a potential system for launch support. The 3-D electric field dataset would complement data provided by the dual-polarization weather radar that will be implemented in the near future. This will provide a capability to continuously study the weather conditions that produce electric fields strong enough to trigger a lightning strike. These datasets can then be used as the basis to revise the lightning-related launch commit criteria on a more frequent basis.

Supplementing this capability would be a more proactive method of determining a lightning threat by using remote measurement of the electric potential along the predicted flight path. This would allow determination on the day of launch/landing whether electric fields in clouds aloft pose a threat of triggered lightning, thus eliminating unnecessary scrubs and delays. For example, recent development of Sonic Lightning Locator (SOLLO) Weather Measurement resulted in proof of concept of a real-time system for determining the accurate (within meters) location of a lightning strike and the intensity of the associated electric and magnetic fields. It is very important to understand the intensity and location of lightning strikes around launch vehicles and payloads to determine the potential for damage caused by induced fields. Furthermore, this technology will help determine the amount of re-test required in such vehicles and payloads due to lightning events.

Important improvements are possible in the avionics software that provides in-flight, 4-D trajectory replanning and commands to the pilot or autopilot. These require additional weather information to minimize the impact of weather on the control of flight. Basic research is needed to determine the most cost-effective way of integrating real-time weather information into 4-D, integrated control of flight.

2.4.4. Robotics/Telerobotics

Launch and ground processing activities will be facilitated through the use of robotic agents controlled by humans, working with humans or functioning as independent agents on tasks not requiring human supervision. Robotic agents will help reduce workforce requirements by performing simple or repetitive operations. Robotic agents will also assist by working in environments or performing tasks hazardous to humans. For example, during ground launch operations, it is hazardous for humans to be in the pad environ once fueling operations have begun, yet it is not atypical for problems to occur, requiring functions to be performed, such as the torquing of valves, reactivation of tripped breakers or inspection of equipment. The need to perform such functions in hazardous conditions often leads to delays or can result in scrubs. Robotic agents will reduce the risk to humans and decrease the need for delays and scrubs by assisting with or performing functions in hazardous conditions, such as retrieving samples, handling hazardous or toxic materials, removing foreign object or other debris, securing or reconfiguring hardware, conducting inspections or repairs, or even assisting injured humans.

This TA has defined the need for 3-D modeling of instruments, materials, and structures; 3-D modeling of robotic observations in relevant domains; planning of robotic operations; machine vision and object recognition; smart cameras; virtual control; remote inspection, servicing, maintenance and repair capability; and remote and autonomous hazardous and nonhazardous operations. Technologies will be developed and integrated to perform tele-operated and autonomous robotics operations, such as large acreage damage and defect inspection, maintenance and repair, and vehicle safing and servicing in processing facilities and at the launch pad and landing site. Supporting strategies will be met via TA-4 (Robotics, Telerobotics, and Autonomous Systems) road maps.

2.4.5. Safety Systems

Many functions within the area of operations/institutional safety (such as inspections, analysis, and approvals) are still labor-intensive and analyses of results are often subjective. Automation and integration of safety functions with ground/launch operations processes will allow integrated planning and analysis, which in turn will provide for safer operations and decrease the risk of a costly mishap, accident, schedule slip, injury, or even death.

Several technologies identified to facilitate safer, integrated operations include:

- Radio-frequency identification applied to products, equipment, materials or personnel for the purpose of monitoring and tracking hazardous materials, critical parts, or personnel.
- A "virtual range" to enable range safety analysis and planning for existing and future ground/launch operations, both nominal and off-nominal, using different weather conditions, vehicle configurations, etc.
- Wireless or optical networks and portable computing devices to allow personnel to quickly access, generate, or transmit safety data and information.
- Network and computing technologies to allow greater access to electronic data and information from distributed and remote locations.
- Human-system interfaces to enable safety alerts and process interrupts to avoid unsafe conditions.
- Integrated health management to enable identification of and recovery from critical system failures.
- Ground/launch architectures to enable integration of automated safety functions with other ground/launch and range operations.
- Robotic systems to perform hazardous operations, decreasing risk to humans.

Safety and risk assessment and management technologies will be developed to automate the assessment of ground/launch processes and range operations to identify potential risks and hazards and recommend corrective action. Designers and operations personnel will be informed of product safety violations in existing or future systems designs by developing capabilities that integrate the results of automated on-the-spot component failure analyses and electronic queries of repositories with ground/launch processes and range operations. Automated/ autonomous hardware and software "safety sentinels," incorporating proximity sensor, hover-scanner, and intelligent software agent technology, need to be developed and integrated with process monitoring capabilities to perform automated surveillance, automatically alert personnel and inform automated processes for recording significant events, or hazardous, out-of-tolerance conditions. Human performance models need to be developed and integrated with ground/launch process simulations, allowing assessment of complex human-system interactions and identification/mitigation of safety vulnerabilities.

Halons contribute to global warming and ozone depletion, and production has been banned by international agreement. Conventional halon replacements have either been ineffective or have contributed to global warming or ozone depletion. NASA is one of the country's largest remaining users of Halon 1301 for fire protection of critical flight hardware systems. Alternative technologies need to be developed for nontoxic, highly effective, environmentally safe flame retardants for fire suppression. Some limited success has been achieved with water mist. However, delivery of micro-size water droplets is difficult, since much of the water evaporates before it reaches the base of the fire. In addition, water alone only acts to cool the flame and displace oxygen. Water does not inhibit the propagation of the combustion process. Technologies like microencapsulation can be used to encapsulate either multi functional materials or materials in separate microcapsules, which have been specifically formulated to provide fire suppression and extinguishing properties. The microcapsule shell needs to be formulated to deliver the contents of the core on-demand, when needed.

Many of the propellants used aboard U.S. launch vehicles and spacecraft, as well as other commodities used in ground systems are toxic. Protective measures must be provided to personnel who handle these agents and those who respond to spills or other emergencies. Fully encapsulated suits with a self-contained breathing apparatus are critical for providing respiratory and skin protection. The conventional apparatus stores the breathing medium, generally air, as a compressed gas. However, this old technology relies upon heavy, high-pressure cylinders that must be carried by the user or firefighter. In addition, these suits expose the user to very warm gas, which can cause heat stress during warm weather. In the mid-1980s, a liquid air breathing apparatus was implemented to support extended duration work, while maintaining a similar or slightly lower backpack weight. Advanced technologies are needed to reduce the bulkiness of these protective suits, reduce cost, expedite job performance, extend canister duration limits, and improve safety during these hazardous operations. The current suit's thermal control system requires an airflow around the wearer, resulting in a bulky suit. Phase change material technologies for passive thermal control can be developed to enable the suit and gloves to be more like a tight-fitting diver's wetsuit. A supercritical cryogenically supplied breathing apparatus and cooled-suit technologies are needed to eliminate problems with oxygen enrichment, orientation dependence, and suit weight while enhancing the safety and comfort of the closed-circuit system. Other types of personnel protective equipment (PPE) and remediation equipment, such as face shields, protective suits without an air supply, and scuppers, also require technology advancements. Additional issues to be addressed with advanced PPE technologies include: user dexterity/agility/flexibility, accommodation of a wide anthropometric range without degrading operator performance, electrostatic discharge, visibility, audio communication, and integration of suit technologies with electronic work instruction systems.

3. INTERDEPENDENCY WITH OTHER TECHNOLOGY AREAS

Table 1 identifies areas of synergy or overlap with the other technology areas. Team 13 believes that TAs 4, 5, 7, and 11 may have the most synergy or overlap. Note: Because most TA teams have listed some form of automated control, FDIR, and communication technologies for their areas, those were not listed in this table.

4. POSSIBLE BENEFITS TO OTHER NATIONAL NEEDS

As defined by the Office of Science and Technology Policy, "Scientific discovery and technology innovation are major engines of increasing productivity and are indispensable for promoting economic growth, safeguarding the environment, improving the health of the population and safeguarding our national security in the technologically driven 21st century."

For energy conservation, developing green products, materials, and processes (e.g., alternative solvents through green chemistry and incorporation of living plants into "green" roof and walls structures) will offer broad benefits for building and manufacturing industries. Alternate energy sources and energy harvesting technologies (e.g., waste disposal, lightning capture, and radio frequency waste-driven power, harnessing the launch energy, and cost-effective green diesel) reduce our nation's dependence on fossil fuels, coal-fired power plants, and energy imports.

For the environment, environmentally friendly

Table 1. *Interdependencies with other technology areas*

TA-1 — Launch Propulsion Systems	
Alternate Propulsion technologies (kerosene, LOX/CH4)	Ground systems for new launch technologies
TA-2 — In-Space Propulsion Systems	
Long-term cryogenic propellant storage and transfer	
TA-4 — Robotics, Telerobotics, and Autonomous Systems	
Distributed collaboration	Multiagent coordination
Modeling/simulation	Immersive visualization
Supervision across time delay	Autonomous planning and scheduling of resources
TA-5 — Communication and Navigation Systems	
Telemetry systems using new spectrum	Range safety
Secure access	Space-based range
On-demand frequency allocation (cognitive radios)	Communication through plume
Adaptive data compression	Self-panning interspacecraft communications
Intelligent network topologies (DTN)	Natural language/universal translator
Interspacecraft communications	Intelligibility of voice communication
Universal communications beacon for hailing	Precision timing sources
TA-7 — Human Exploration Destination Systems	
Virtual reality/training	Real time mission ops replanning
High-bandwidth communications	Modeling tools
Reconfigurable operations	Simulation tools
Intelligent (software) controls	Self-healing technologies
TA-10 — Nanotechnology	
Damage-tolerant systems	Self-diagnosing materials
Self-repairing materials	
TA-11 — Modeling, Simulation, Information Technology, and Processing	
Multisector planning functions	Seamless/high-accessibility data and info flow
System-level capabilities	Peer-to-peer communication
Simulation-to-implementation for mission ops automation	Flexible metadata generation, content, and organization
Onboard simulation-based training/decision support	Automated data validation and quality assessment
Automatic fault and recovery simulation	Usable secure system
End-to-end spacecraft data-proc & discovery framework	Evolutionary data networking, storage, and access
TA-12 — Materials, Structures, Mechanical Systems, and Manufacturing	
Thermal protection	Composite materials repair
Lightweight/self-healing materials	Environmentally hardened materials
Nondestructive evaluation	Damage tolerance of composite cases

remediation technologies for waste and hazardous materials (e.g., green processes for pollution/contaminant removal and safe disposal of waste) can provide national benefits for cost-effective, rapid-response cleanup of environmental contaminants. Commercial applications include treating contamination from gas stations, dry cleaning operations, and chemical manufacturers. Carbon sequestration technologies (e.g., concrete aggregates and binders that sequester carbon dioxide without losing strength) offer alternatives to industry for mitigating the impact of climate change.

"Corrosion is a silent killer of the world's critical infrastructure (water and wastewater systems, bridges, energy distribution systems, storage tanks, nuclear facilities, etc.). In a recent report, the World Corrosion Organization stated that corrosion costs the world economy over $2 trillion annually. This threatens our way of life and challenges us to be more proactive in addressing the problem. We can no longer wait to address corrosion." (From Oil and Gas Eurasia, September 9, 2010.) Development of environmentally friendly corrosion-resistant/protective and self-healing materials, coatings, and structures can provide international benefits for decreasing the substantial costs corrosion-related damage and enable compliance with increasingly stringent EPA regulations for use of volatile organic compounds/hazardous air pollutants, emission standards, human exposure limits, and waste disposal requirements. These new materials have potential application throughout the Department of Defense (DoD) in military weapon systems, Army ground vehicles, and Navy ships; the oil and gas industry; automotive, the building, manufacturing, and housing industries; the paint industry; and the degrading transportation infrastructure.

Technologies included in this roadmap support a number of initiatives of other government agencies, such as development of insulated piping to enable high-temperature superconducting (HTS) power cables to be implemented in the U.S. for the future Resilient Electric Grid program and to be used for degaussing of sensors on littoral combat ships; flexible cryogenic piping (cryostats) to enable a U.S.-based manufacturing capability for long-length, flexible, vacuum-jacketed, multilayer insulated, cryogenic piping; and material insulation technologies for energy and cost efficiencies in many industrial sectors including oil and gas, transportation, military, apparel, and building construction.

Range systems development has the potential to provide security benefits for the DoD and Department of Homeland Security (DHS). Weather technologies developed for prediction, mitigation, and informed decision making in GLSP will have extended applications and benefits to every element of society that relies on federal and regional/local weather forecasting for protection against inclement weather.

Self-diagnosing, self-healing wiring technologies have enormous crosscutting applications for aerospace, defense, and aviation industries that have significant system wiring issues. Electrical wiring is integral to communication, control and navigation in vehicles, and provides the infrastructure that fully links electrical, electro-mechanical, and electronic systems. Hence, system safety is integrally linked to the wiring performance. Aging wiring materials in flight and ground systems have contributed to excessive operations and maintenance costs, caused wire insulation failures in critical electrical and communications systems, compromised mission/aircraft safety, and in some cases, caused catastrophic system failures that resulted in loss of life. Virtually all systems that rely on power, control, and communications stand to benefit tremendously from development of wiring that is multifunctional, adaptive, and self-healing in response to changing mission conditions on the ground and in-flight. Substantial improvements in system reliability and safety during processing and flight operations, and reductions in time and costs related to ground processing diagnostics and repair will be a direct result of these innovations.

Ground based electromagnetic launch (EML) assist is cross-cutting technology development aimed at improving NASA, other government, and commercial space capabilities for guided surface transportation (urban low-speed and intercity high-speed); highways (zero-emission linear motor systems to reduce emissions and improve fuel economy of traditional vehicles, and enable unlimited range for electric vehicles); electric power storage, coupling, recharging, and regeneration systems; and next generation and green aviation (linear motors for taxiing, inductive power coupling for zero-emission idling, EML takeoff and landing with power regeneration).

The defense industry seeks to develop spacecraft, launch vehicles, and ground processes that are more responsive to war fighting needs. Desired systems will be easier to operate and will require less operator training and cryogenic expertise while ground processes will require less time. Many of the technologies included in this TA, such as intelligent devices, cryogenic components, pumping techniques to decrease the time for cryogenic fueling operations. Self-healing devices and materials, health management technologies, spaced-based range, optical communications and autonomous flight termination support these industries by providing more rapid vehicle turnaround and access to space through robust ground and vehicle systems, portable or remotely accessible checkout, command, control and decision support systems, and autonomous operations.

5. NATIONAL RESEARCH COUNCIL REPORT

The earlier sections of this document were completed and issued publicly in December, 2010. NASA subsequently tasked the Aeronautics and Space Engineering Board of the National Research Council of the National Academies to perform the following tasks:

- **Criteria:** Establish a set of criteria to enable prioritization of technologies within each and among all of the technology areas that the NASA technology roadmaps should satisfy;
- **Technologies:** Consider technologies that address the needs of NASA's exploration systems, Earth and space science, and space operations mission areas, as well as those that contribute to critical national and commercial needs in space technology;
- **Integration:** Integrate the outputs to identify key common threads and issues and to summarize findings and recommendations; and
- **Prioritization:** Prioritize the highest-priority technologies from all 14 roadmaps.

In addition to a final report that addressed these tasks, NASA also tasked the NRC/ASEB with providing a brief interim report that "addresses high-level issues associated with the roadmaps, such as the advisability of modifying the number or technical focus of the draft NASA roadmaps."

In August, 2011, the NRC/ASEB delivered "An Interim Report on NASA's Draft Space Technology Roadmaps" which, among other things, verified the adequacy of the fourteen Technology Areas as a top-level taxonomy, proposed changes in the technology area breakdown structure (TABS) within many of the TA's, and addressed gaps in the draft roadmaps that go beyond the existing technology area breakdown structure.

On February, 1, 2012, the NRC/ASEB delivered the final report entitled “NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES: Restoring NASA’s Technological Edge and Paving the Way for a New Era in Space”. The report prioritizes (e.g., high, medium, low) the technologies **within** each of the 14 Technology Areas, and also prioritizes **across** all 14 roadmaps [highest of the high technologies].

The remainder of this section summarizes:

- The changes that the NRC recommended to the TABS presented earlier in this document
- The NRC prioritization of the technologies in this TA, as well as highlights any of this TA’s technologies that the NRC ranked as a ‘highest of high’ technology.
- Salient comments and context, quoted verbatim, from the NRC report that provide important context for understanding their prioritization, findings, or recommendations.

5.1. NRC Recommended Revisions to the TABS

In both the interim and the final report, the NRC Panel did not recommend changes to the TA#13 TABS, which was submitted as follows:

TA13 Ground & Launch Systems Processing

13.1. Technologies to Optimize the Operational Life-Cycle

13.1.1. Storage, Distribution & Conservation of Fluids

13.1.2. Automated Alignment, Coupling, & Assembly Systems

13.1.3. Autonomous Command & Control for Ground and Integrated Vehicle/Ground Systems

13.2. Environmental and Green Technologies

13.2.1. Corrosion Prevention, Detection, & Mitigation

13.2.2. Environmental Remediation & Site Restoration

13.2.3. Preservation of Natural Ecosystems

13.2.4. Alternate Energy Prototypes

13.3. Technologies to Increase Reliability and Mission Availability

13.3.1. Advanced Launch Technologies

13.3.2. Environment-Hardened Materials and Structures

13.3.3. Inspection, Anomaly Detection & Identification

13.3.4. Fault Isolation and Diagnostics

13.3.5. Prognostics Technologies

13.3.6. Repair, Mitigation, and Recovery Technologies

13.3.7. Communications, Networking, Timing & Telemetry

13.4. Technologies to Improve Mission Safety/Mission Risk

13.4.1. Range Tracking, Surveillance & Flight Safety Technologies

13.4.2. Landing & Recovery Systems & Components

13.4.3. Weather Prediction and Mitigation

13.4.4. Robotics / Tele-robotics

13.4.5. Safety Systems

5.2. NRC Prioritization

The draft TA13 Roadmap is divided into 19 Level 3 technologies, and, like some other TAs, they typically encompass a variety of systems, subsystems, and components, with multiple potential implementation solutions.

Table 2 lists the overall NRC Panel rankings for the TA#13 Level 3 technologies, none of which were identified in the NRC report as “High priority”. This is in conflict with some other recent technology assessments against the TA#13 Draft Roadmap report. Also, it appears to conflict with the high prioritization appropriately given by the NRC to complimentary technologies in some of the other NASA OCT Roadmaps. An example of this is where the Ground Computing, Flight Computing, and Distributed Simulation Technology areas from TA#11 were appropriately assessed as high priority technologies, albeit by a different NRC Sub-Panel, whereas the “Autonomous Command and Control for Ground and Integrated Vehicle/Ground Systems” which integrates these computing and simulation technologies, was assessed as a “low priority.

5.3. Additional / Salient Comments from the NRC Reports

To place the priorities, findings, and recommendations in context for this TA, the following quotes from the NRC reports are noteworthy; excerpts from other sections of the NRC report that correspond to or compliment Ground and Launch Systems Processing are annotated accordingly:

- “Advances in ground and launch systems processing implies overcoming several challenges, such as reducing the cost of maintaining and operating ground control

Table 2. *Prioritization of TA13 Level 3 Technologies*

TABS #	TABS Title	NRC Prioritization	Notes
13.1.1	Storage, Distribution & Conservation of Fluids	MEDIUM	Assessed by **both** the NASA Engineering Safety Center (NESC), and by the Human Spaceflight Architecture Team (HAT) as a "High" Priority
13.1.2	Automated Alignment, Coupling, & Assembly Systems	LOW	
13.1.3	Autonomous Command & Control for Ground and Integrated Vehicle/ Ground Systems	LOW	Assessed by the NASA Engineering Safety Center (NESC) as a "High" Priority
13.2.1	Corrosion Prevention, Detection, & Mitigation	MEDIUM	Assessed by **both** the NASA Engineering Safety Center (NESC), and by the Human Spaceflight Architecture Team (HAT) as a "High" Priority
13.2.2	Environmental Remediation & Site Restoration	LOW	
13.2.3	Preservation of Natural Ecosystems	LOW	
13.2.4	Alternate Energy Prototypes	LOW	
13.3.1	Advanced Launch Technologies	LOW	
13.3.2	Environment-Hardened Materials and Structures	LOW	
13.3.3	Inspection, Anomaly Detection & Identification	MEDIUM	Assessed by **both** the NASA Engineering Safety Center (NESC), and by the Human Spaceflight Architecture Team (HAT) as a "High" Priority
13.3.4	Fault Isolation and Diagnostics	MEDIUM	Assessed by the NASA Human Spaceflight Architecture Team (HAT) as a "High" Priority
13.3.5	Prognostics Technologies	MEDIUM	
13.3.6	Repair, Mitigation, and Recovery Technologies	MEDIUM	
13.3.7	Communications, Networking, Timing & Telemetry	MEDIUM	
13.4.1	Range Tracking, Surveillance & Flight Safety Technologies	MEDIUM	
13.4.2	Landing & Recovery Systems & Components	LOW	
13.4.3	Weather Prediction and Mitigation	MEDIUM	Assessed by the NASA Engineering Safety Center (NESC) as a "High" Priority
13.4.4	Robotics / Tele-robotics	LOW	
13.4.5	Safety Systems	MEDIUM	Assessed by the NASA Engineering Safety Center (NESC) as a "High" Priority

and launch infrastructure, improving safety, and improving the timeliness, relevance, and accuracy of information provided to ground control and launch personnel"

- "One major barrier to any space mission is the high cost of access to space. In spite of billions of dollars in investment over the last several decades, the cost of launch has not decreased. In fact, with the end of the Space Shuttle Program and uncertainty in the future direction in human spaceflight, launch costs for NASA science missions are actually increasing. This is because without the space shuttle or a human spaceflight program, the propulsion industrial base is at significant overcapacity. The resulting high costs limit both the number and scope of NASA's space missions. Finding technologies that dramatically reduce launch cost is a tremendous challenge given the past lack of success. (From TA#01 Appendix)

- "Reliability and safety continue to be major concerns in the launch business. For NASA space missions, the cost of failure is extreme. Finding ways to improve reliability and safety without dramatically increasing cost is a major technology challenge. (From TA#01 Appendix)
- "The panel combined the related and overlapping topics of integrated systems health management (ISHM), fault detection and isolation and recovery (FDIR), and vehicle systems management (VSM). Together these algorithms provide the crucial capability for an autonomous spacecraft to operate safely and reliably, even in the face of changing mission objectives and/or vehicle failures. ISHM/FDIR/VSM will improve the reliability of future missions by providing a diagnostic capability that helps ground or crew failure assessment and an automated capability to fix/overcome faults; increasing robotic mission flexibility in response to failures; and increasing crew safety in the event of a detected need for crew escape and abort." (From TA#04 Appendix)
- "Advanced portable life support systems are applicable to firefighters, hazmat suits, bio-warfare gear, and underwater breathing systems. The particular focus for NASA technology development (in terms of thermal control without sublimation and extremely high-reliability systems where cost is relatively unimportant) are unique to the NASA mission." (From TA#06 Appendix)
- "The complexity of systems comprised of advanced hardware and software must be managed in order to ensure the systems' reliability and robustness. New software tools that allow insight into the design of complex systems will support the development of systems with well understood, predictable behavior while minimizing or eliminating undesirable responses." (From TA#11 Appendix)
- "Distributed simulation technologies create the ability to share simulations between software developers, scientists, and data analysts, and thus, greatly enhance the value of the large investments of the simulation, which currently can require tens of millions of CPU hours. There is a need for large scale, shared, secure, distributed environments with sufficient interconnect bandwidth and display capabilities to enable distributed simulation (processing) as well as distributed analysis and visualization of data produced by simulations." (From TA#11)
- "Mission assurance would be enhanced by an integrated structural health monitoring system that could detect and assess the criticality of in-service damage or fault, then define an amelioration process or trigger a repair in self-healing structures. Such a system requires light, reliable, rugged, unobtrusive and multifunctional sensors that can be integrated into the structure along with power and data transmission capability. Software to combine disparate data, to diagnose and predict structural health, and to enable the necessary repairs is also a significant challenge." (From TA#12)
- "Accelerate research on advanced active and passive systems to approach near-zero boil-off in long-term cryogenic storage." (From TA#14)

  " …advances in ground support technology would improve mission assurance as well as launch reliability and safety, particularly if a large data set is collected during the vehicle development and early testing."

A specific finding in the NRC report addresses facilities; the following quotes are specific to this TA.

- "Adequate research and testing facilities are essential to the timely development of many space technologies. In some cases, critical facilities do not exist or no longer exist…" "… the health and availability of facilities is closely linked to development of advanced technology."

ACRONYMS

3-D	three-dimensional
AGV	Automated Guided Vehicles
AMPM	Agency Mission Planning Manifest
CAD	computer-aided design
CAE	computer-aided engineering
C&DH	command and data handling
CDC	Centers for Disease Control
COTS	commercial off-the-shelf
DHS	Department of Homeland Security
DoD	Department of Defense
DNAPL	dense, non-aqueous phase liquid
DRA	Design Reference Architecture
DRM	Design Reference Mission
DTN	Data Transmission Network
ELV	Expendable Launch Vehicle
EML	electromagnetic launch
EPA	Environmental Protection Agency
ETDP	Exploration Technology Development Program
EZVI	emulsified zero valent iron
FDIR	fault detection, isolation and recovery
FY	fiscal year
GDP	Gross Domestic Product
GLSP	Ground and Launch Systems Processing
GLTD	Ground and Launch Technology Demonstration
GSE	ground support equipment
HAP	hazardous air pollutant
HCI	human-computer interface
He	helium
IMP	intermetallic phase
IRL	Integration Readiness Level
ISHM	Integrated System Health Management
ISRU	in-situ resource utilization
ISS	International Space Station
IT	information technology
IVHM	Integrated Vehicle Health Management
JPDO	Joint Projects Development Office
LDAR	lightning detection and ranging
LEED	Leadership in Energy and Environmental Design
LEO	low-Earth orbit
LH_2	liquid hydrogen
LOX	liquid oxygen
M	million
MLI	multilayer insulation
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NDE	nondestructive evaluation
NBP	normal boiling point
PC	personal computer
PDA	personal data assistant
PEL	permissible exposure limit
PPE	personnel protective equipment
POD	portable on-demand
QD	quick disconnect
RF	radio frequency
ROM	rough order of magnitude
ROI	return on investment
RLV	Reusable Launch Vehicle
RTG	radioisotope thermoelectric generator
SAS	Single Authoritative Source
SITE	Superfund Innovative Technology Evaluation
S&MA	Safety and Mission Assurance
SOLLO	Sonic Lightning Locator
SRL	System Readiness Level
TA	technology area
TABS	Technology Area Breakdown Structure
TPS	Thermal Protection System
TReK	Telescience Research Kit
TRL	Technology Readiness Level
U.S.	United States
VOC	Volatile Organic Compound
WIDB	Weather Information Database

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